

Solutions Manual

Engineering Fundamentals of the Internal Combustion Engine Second Edition

Willard W. Pulkrabek
University of Wisconsin-Platteville



Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

Acquisitions Editor: Laura Fischer
Supplement Editor: Andrea Messineo
Executive Managing Editor: Vince O'Brien
Managing Editor: David A. George
Production Editor: Barbara A. Till
Supplement Cover Manager: Daniel Sandin
Manufacturing Buyer: Ilene Kahn



© 2004 by Pearson Education, Inc.
Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, NJ 07458

All rights reserved. No part of this book may be reproduced in any form or by any means, without permission in writing from the publisher.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

Pearson Prentice Hall® is a trademark of Pearson Education, Inc.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-141035-0

Pearson Education Ltd., *London*
Pearson Education Australia Pty. Ltd., *Sydney*
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd., *Hong Kong*
Pearson Education Canada, Inc., *Toronto*
Pearson Educación de México, S.A. de C.V.
Pearson Education—Japan, *Tokyo*
Pearson Education Malaysia, Pte. Ltd.
Pearson Education, Inc., *Upper Saddle River, New Jersey*

Contents

1	Introduction	1
2	Operating Characteristics	6
3	Engine Cycles	19
4	Thermochemistry and Fuels	36
5	Air and Fuel Induction	51
6	Fluid Motion Within Combustion Chamber	63
7	Combustion	70
8	Exhaust Flow	76
9	Emissions and Air Pollution	82
10	Heat Transfer in Engines	95
11	Friction and Lubrication	103

CHAPTER 1

(1-1)

**SI engines use spark plugs.
CI engines use self-ignition.**

**SI engines intake an air-fuel mixture.
CI engines intake air only.**

**SI engines have combustion at about constant volume.
CI engines have some combustion at about constant pressure.**

**SI engines use gasoline fuel.
CI engines use diesel oil fuel.**

**SI engines use carburetors or fuel injectors in the intake system.
CI engines have fuel injectors in the combustion chamber.**

(1-2)

Two stroke cycle engines have no exhaust stroke. Excess exhaust must be pushed out of cylinder (scavenged) by the intake air-fuel mixture (or intake air in CI engines). This requires that the intake mixture be at a higher pressure than the exhaust residual.

(1-3)

Advantages of two stroke cycle:

**Smoother cycle with a power stroke from every cylinder on every revolution.
Do not need mechanical valves.
More power from same weight engine.**

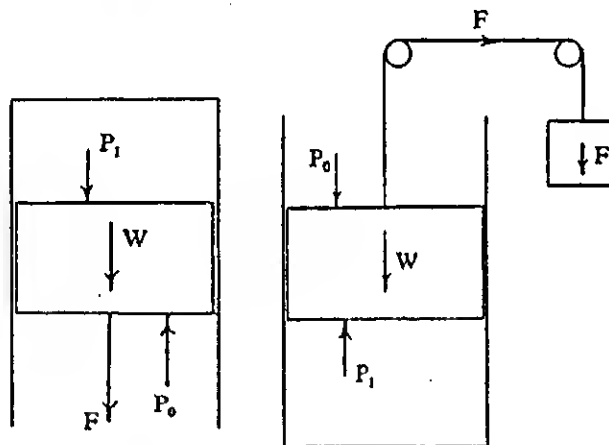
Advantages of four stroke cycle:

**Can operate without an intake pressure boost.
Cleaner operation with less exhaust pollution.
Can use crankcase for oil reservoir.**

(1-4)

- (a) They do not need mechanical valves. Valve mechanism for a very small engine would need to be high precision and costly. With no valves engines can be made cheaper and lighter which is very desirable for small engines.
- (b) Very large engines operate at a very low RPM. Because of this they need a power stroke from every cylinder during every revolution to have a smooth operating cycle.
- (c) Because of large valve overlap there is too much pollution in the exhaust of a two stroke cycle engine. They cannot pass automobile emission standards required by law.
- (d) More power can be obtained from the same weight engine.

(1-5)



- (a) weight of piston

$$W = mg/g_c = [(2700 \text{ kg})(9.81 \text{ m/sec}^2)]/[(1 \text{ kg-m/N-sec}^2)(1000 \text{ N/kN})] = 26.487 \text{ kN}$$

forces down = forces up

$$P_1(\text{piston face area}) + \text{weight} + F = P_0(\text{piston face area})$$

$$(22 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2] + (26.487 \text{ kN}) + F = (98 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2]$$

$$F = 59.5 \text{ kN} = mg/g_c = m(9.81)/(1)(1000)$$

$$\underline{m = 6062 \text{ kg}}$$

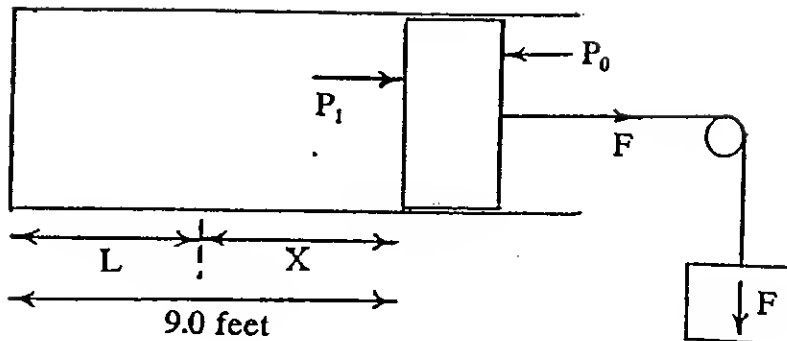
- (b) $P_0(\text{piston face area}) + \text{weight} = F + P_1(\text{piston face area})$

$$(98 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2] + (26.487 \text{ kN}) = F + (22 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2]$$

$$F = 112.441 \text{ kN} = mg/g_c = m(9.81)/(1)(1000)$$

$$\underline{m = 11,462 \text{ kg}}$$

(1-6)



- (a) after combustion air in cylinder cools at constant volume
pressure in cylinder P_1 when piston is first unlocked

$$P_1 = P_0(T_0/T_{\text{comb}}) = (14.7 \text{ psia})(530/1000) = 7.8 \text{ psia}$$

balance of forces on piston

$$P_1(\text{piston face area}) + F = P_0(\text{piston face area})$$

$$[(7.8)(144) \text{ lbf/ft}^2][(\pi/4)(3.2 \text{ ft})^2] + F = [(14.7)(144) \text{ lbf/ft}^2][(\pi/4)(3.2 \text{ ft})^2]$$

$$\underline{F = 7991 \text{ lbf}}$$

- (b) cylinder volume before cooling

$$V_1 = (\pi/4)B^2S = (\pi/4)(3.2 \text{ ft})^2(9 \text{ ft}) = 72.38 \text{ ft}^3$$

with no load piston will move at constant temperature

until cylinder pressure $P_2 = P_0 = 14.7 \text{ psia}$

$$V_2 = V_1(P_1/P_2) = (72.38 \text{ ft}^3)(7.8/14.7) = 38.41 \text{ ft}^3$$

after piston movement

$$V_2 = (\pi/4)(3.2 \text{ ft})^2L = 38.41 \text{ ft}^3 \quad L = 4.78 \text{ ft}$$

distance piston moves X = effective power stroke

$$X = 9 - 4.78 = \underline{4.22 \text{ ft}}$$

- (c) cylinder volume at end of power stroke

$$\underline{V_2 = 38.41 \text{ ft}^3} \quad \text{from above}$$

(1-7)

- (a) Shorter engine length allows for shorter engine compartment.

Shorter crankshaft will have less bending stress.

- (b) Smaller diameter cylinders will have shorter flame travel distance.

Smoother engine cycle with more power strokes per revolution.

- (c) Less mechanical friction in engine.

Larger cylinder volume/surface area ratio giving less heat loss per cycle.

- (d) Lower engine height.

Shorter engine length.

Shorter engine crankshaft.

- (e) Smoother engine cycle with more power strokes per revolution.

Smaller diameter cylinders will have shorter flame travel distance.

(1-8)

- (a) as a radial engine rotates every other cylinder fires
giving 4.5 ignitions and power strokes per revolution

$$(360^\circ/\text{rev})/(4.5 \text{ ignitions/rev}) = \underline{80^\circ/\text{ignition}}$$

- (b) 4.5 power strokes/rev

- (c) $(4.5 \text{ power strokes/rev})(900/60 \text{ rev/sec}) = \underline{67.5 \text{ power strokes/sec}}$

(1-9)

(a) standard automobile

$$m_f = (16,000 \text{ miles}) / (31 \text{ miles/gal}) = \underline{516.1 \text{ gal}}$$

hybrid automobile

$$m_f = (16,000 \text{ miles}) / (82 \text{ miles/gal}) = \underline{195.1 \text{ gal}}$$

$$(b) (516.1) - (195.1) = (321.0 \text{ gal/year}) (\$1.65) = \underline{\$529.65/\text{year}}$$

(c) difference in cost

$$(\$32,000) - (\$18,000) = \$14,000$$

$$t = (\$14,000) / (\$529.65/\text{year}) = \underline{26.4 \text{ years} = 317 \text{ months}}$$

CHAPTER 2

(2-1)

(a) $[(171,000 \text{ miles})(60 \text{ min/hr})(1700 \text{ rev/min})]/(40 \text{ miles/hr}) = \underline{4.36 \times 10^8 \text{ rev}}$

(b) $(4.36 \times 10^8 \text{ rev})(4 \text{ firings/rev}) = \underline{1.744 \times 10^9 \text{ firings}}$

(c) there are same number of Intake strokes as spark plug firings

$(1.744 \times 10^9 \text{ intake strokes/engine})/(8 \text{ cyl/engine}) = \underline{2.18 \times 10^8 \text{ strokes/cyl}}$

(2-2)

(a) Eq. (2-9)

$V_d = N_c(\pi/4)B^2S = (4 \text{ cyl})(\pi/4)(10.9 \text{ cm})^2(12.6 \text{ cm}) = \underline{4703 \text{ cm}^3 = 4.703 \text{ L}}$

(b) Eq. (2-2)

$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.126 \text{ m/stroke})(2000/60 \text{ rev/sec}) = \underline{8.40 \text{ m/sec}}$

Eq. (2-15)

$A_p = (\pi/4)B^2N_c = (\pi/4)(0.109 \text{ m})^2(4 \text{ cyl}) = \underline{0.0373 \text{ m}^2}$

Eq. (2-46)

$W_b = (\text{bmep})A_p\bar{U}_p/2$

$88 \text{ kW} = (\text{bmep})(0.0373 \text{ m}^2)(8.40 \text{ m/sec})/2$

$\underline{\text{bmep} = 561 \text{ kPa}}$

or using Eq. (2-88)

$\text{bmep} = (1000)(88)(1)/(4.703)(2000/60) = \underline{561 \text{ kPa}}$

(c) Eq. (2-40)

$\tau = (\text{bmep})V_d/2\pi = (561 \text{ kPa})(0.004703 \text{ m}^3)/2\pi = \underline{0.420 \text{ kN}\cdot\text{m} = 420 \text{ N}\cdot\text{m}}$

or using Eq. (2-76)

$\tau = (159.2)(88)/(2000/60) = \underline{420 \text{ N}\cdot\text{m}}$

(d) for one cylinder

$V_d = (4703 \text{ cm}^3)/4 = \underline{1176 \text{ cm}^3}$

Eq. (2-12)

$r_c = (V_d + V_c)/V_c = 18 = (1176 + V_c)/V_c$

$\underline{V_c = 69.2 \text{ cm}^3}$

(2-3)

(a)

for one cylinder

$$V_d = (2.4 \text{ L})/4 = 0.6 \text{ L} = 600 \text{ cm}^3$$

Eq. (2-12)

$$r_c = (V_d + V_c)/V_c = 9.4 = (600 + V_c)/V_c$$

$$\underline{V_c = 71.43 \text{ cm}^3 = 0.07143 \text{ L} = 4.36 \text{ in.}^3}$$

(b)

Eq. (2-8)

$$V_d = 600 \text{ cm}^3 = (\pi/4)B^2S = (\pi/4)B^2(1.06 B)$$

$$\underline{B = 8.97 \text{ cm} = 3.53 \text{ in.}}$$

$$S = 1.06 B = (1.06)(8.97 \text{ cm}) = \underline{9.50 \text{ cm} = 3.74 \text{ in.}}$$

(c)

Eq. (2-2)

$$\begin{aligned} \bar{U}_p &= 2SN = (2 \text{ strokes/rev})(0.0950 \text{ m/stroke})(3200/60 \text{ rev/sec}) \\ &= \underline{10.13 \text{ m/sec} = 33.2 \text{ ft/sec}} \end{aligned}$$

(2-4)

Advantages of over square engine:

For the same cylinder displacement volume an over square engine will have a shorter stroke length. This will result in a lower average piston speed and lower friction losses.

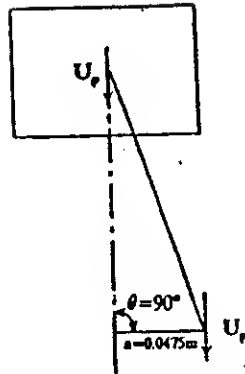
Cylinder lengths will be slightly shorter.

Advantages of under square engine:

An under square engine will have smaller diameter cylinders, resulting in a shorter flame travel distance.

Combustion chamber surface area will be smaller resulting in less heat loss per cycle.

(2-5)



(a) from Problem (2-3) $\bar{U}_p = 10.13 \text{ m/sec}$

- (b) approximate piston speed is as shown
crankshaft offset equals half of stroke length
 $a = S/2 = (0.095 \text{ m})/2 = 0.0475 \text{ m}$

$$U_p = \omega r = [(3200/60)(2\pi) \text{ radians/sec}](0.0475 \text{ m}) = \underline{15.9 \text{ m/sec}}$$

(2-6)

for one cylinder $V_d = (3.5 \text{ L})/5 = 0.7 \text{ L} = 0.0007 \text{ m}^3$

(a) Eq. (2-29)
 $\text{imep} = W/V_d = (1000 \text{ J})/[(0.0007 \text{ m}^3)(1000 \text{ J/kJ})] = \underline{1429 \text{ kPa}}$

(b) Eq. (2-37c)
 $\text{bmep} = \eta_m \text{imep} = (0.62)(1429 \text{ kPa}) = \underline{886 \text{ kPa}}$

(c) Eq. (2-37d)
 $\text{fmep} = \text{imep} - \text{bmep} = (1429 \text{ kPa}) - (886 \text{ kPa}) = \underline{543 \text{ kPa}}$

(d) indicated power using Eq. (2-42)
 $\dot{W}_i = WN/n$
 $= [(1 \text{ kJ/cyl-cycle})(2500/60 \text{ rev/sec})(5 \text{ cyl})]/(2 \text{ rev/cycle}) = 104.2 \text{ kW}$

Eq. (2-47)
 $\dot{W}_b = \eta_m \dot{W}_i = (0.62)(104.2 \text{ kW}) = \underline{64.6 \text{ kW} = 86.6 \text{ hp}}$

or using Eq. (2-81)
 $\dot{W}_b = [(886)(3.5)(2500/60)]/[(1000)(2)] = \underline{64.6 \text{ kW}}$

(e) Eq. (2-41)
 $\tau = (\text{bmep})V_d/4\pi = (886 \text{ kN/m}^2)(0.0035 \text{ m}^3)/4\pi = \underline{247 \text{ N-m}}$

or using Eq. (2-76)
 $\tau = (159.2)(64.6)/(2500/60) = \underline{247 \text{ N-m}}$

(2-7)

Eq. (2-8) for one cylinder

$$V_d = 0.0007 \text{ m}^3 = (\pi/4)B^2S = (\pi/4)B^3$$

$$B = S = 0.0962 \text{ m} = 9.62 \text{ cm}$$

(a)

Eq. (2-51)

$$SP = \dot{W}_b/A_p = \dot{W}_b/[(\pi/4)B^2N_c] = (64.6 \text{ kW})/[(\pi/4)(9.62 \text{ cm})^2(5 \text{ cyl})] = \underline{0.178 \text{ kW/cm}^2}$$

(b)

Eq. (2-52)

$$OPD = \dot{W}_b/V_d = (64.6 \text{ kW})/(3500 \text{ cm}^3) = \underline{0.0185 \text{ kW/cm}^3}$$

(c)

Eq. (2-53)

$$SV = V_d/\dot{W}_b = (3500 \text{ cm}^3)/(64.6 \text{ kW}) = \underline{54.1 \text{ cm}^3/\text{kW}}$$

(d)

Eq. (2-49)

$$\dot{W}_r = \dot{W}_i - \dot{W}_b = (104.2 \text{ kW}) - (64.6 \text{ kW}) = \underline{39.6 \text{ kW} = 53.1 \text{ hp}}$$

(2-8)

(a)

mass flow rate of fuel into engine

$$\dot{m}_f = 0.0060 \text{ kg/sec} \quad \text{from Example Problem 2-4}$$

mass flow of fuel not burned

$$(\dot{m}_f)_{nb} = \dot{m}_f(1 - \eta_c) = (0.0060 \text{ kg/sec})(1 - 0.97)(3600 \text{ sec/hr}) = \underline{0.648 \text{ kg/hr}}$$

(b)

Eq. (2-73)

$$(SE)_{HC} = \dot{m}_{HC}/\dot{W}_b = (648 \text{ gm/hr})/(77.3 \text{ kW}) = \underline{8.38 \text{ gm/kW-hr}}$$

(c)

mass flow of unburned fuel emissions

$$\dot{m}_{HC} = [(0.648 \text{ kg/hr})(1000 \text{ gm/kg})]/(3600 \text{ sec/hr}) = 0.18 \text{ gm/sec}$$

Eq. (2-74)

$$(EI)_{HC} = \dot{m}_{HC}/\dot{m}_f = (0.18 \text{ gm/sec})/(0.0060 \text{ kg/sec}) = \underline{30 \text{ gm/kg}}$$

(2-9)

(a)

Eq. (2-9)

$$V_d = N_c(\pi/4)B^2S = (8 \text{ cyl})(\pi/4)(5.375 \text{ in.})^2(8.0 \text{ in.}) = \underline{1452 \text{ in.}^3}$$

(b)

Eq. (2-15)

$$A_p = (\pi/4)B^2N_c = (\pi/4)(5.375 \text{ in.})^2(8 \text{ cyl}) = 181.5 \text{ in.}^2 = 1.260 \text{ ft}^2$$

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(8/12 \text{ ft/stroke})(1000/60 \text{ rev/sec}) = 22.2 \text{ ft/sec}$$

Eq. (2-45)

$$\dot{W}_b = (\text{bmep})A_p\bar{U}_p/4$$
$$(152 \text{ hp})(550 \text{ ft-lbf/sec/hp}) = (\text{bmep})(1.260 \text{ ft}^2)(22.2 \text{ ft/sec})/4$$

$$\text{bmep} = 11,955 \text{ lbf/ft}^2 = \underline{83.0 \text{ psia}}$$

or using Eq. (2-90)

$$\text{bmep} = [(396,000)(152)(2)]/[(1452)(1000)] = \underline{83.0 \text{ psia}}$$

(c)

Eq. (2-41)

$$\tau = (\text{bmep})V_d/4\pi = (11,955 \text{ lbf/ft}^2)[1452/(12)^3]\text{ft}^3/(4\pi) = \underline{799 \text{ lbf-ft}}$$

or using Eq. (2-77)

$$\tau = (5252)(152)/1000 = \underline{799 \text{ lbf-ft}}$$

(d)

Eq. (2-47)

$$\dot{W}_1 = \dot{W}_b/\eta_m = (152 \text{ hp})/0.60 = \underline{253 \text{ hp}}$$

(e)

Eq. (2-49)

$$\dot{W}_r = \dot{W}_1 - \dot{W}_b = (253 \text{ hp}) - (152 \text{ hp}) = \underline{101 \text{ hp}}$$

(2-10)

(a)

Eq. (2-71)

$$\dot{m}_a = \rho_a V_d \eta_r N/n = (1.181)(0.001500)(0.92)(3000/60)/(2) = \underline{0.0407 \text{ kg/sec}}$$

(b)

rate of fuel into engine using Eq. (2-55)

$$\dot{m}_f = \dot{m}_a / (AF) = (0.0407 \text{ kg/sec})/21 = 0.00194 \text{ kg/sec} = 6.985 \text{ kg/hr}$$

Eq. (2-60)

$$\text{bsfc} = \dot{m}_f / W_b = (6.985 \text{ kg/hr})/(48 \text{ kW}) = 0.1455 \text{ kg/kW-hr} = \underline{145.5 \text{ gm/kW-hr}}$$

(c)

mass flow of exhaust equals air plus fuel

$$\dot{m}_{ex} = [(0.0407)(22/21) \text{ kg/sec}](3600 \text{ sec/hr}) = \underline{153.5 \text{ kg/hr}}$$

(d)

Eq. (2-52)

$$\text{OPD} = \dot{W}_b / V_d = (48 \text{ kW})/(1.5 \text{ L}) = \underline{32 \text{ kW/L}}$$

(2-11)

(a)

Eq. (2-8) for one cylinder

$$V_d = (5 \text{ L})/6 = 0.8333 \text{ L} = 833.3 \text{ cm}^3 = (\pi/4)B^2S = (\pi/4)(0.92)B^3$$

$$B = 10.49 \text{ cm} \quad S = 0.92 B = (0.92)(10.49 \text{ cm}) = \underline{9.65 \text{ cm}}$$

(b)

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.0965 \text{ m/stroke})(2400/60 \text{ rev/sec}) = \underline{7.72 \text{ m/sec}}$$

(c)

Eq. (2-12)

$$r_c = (V_d + V_c)/V_c = 10.2 = (833.3 + V_c)/V_c$$

$$\underline{V_c = 90.6 \text{ cm}^3}$$

(d)

Eq. (2-71)

$$\dot{m}_a = \rho_a V_d \eta_r N/n = (1.181)(0.005)(0.91)(2400/60)/(2) = \underline{0.107 \text{ kg/sec}}$$

(2-12)

(a) $(500 \text{ miles}) / (18 \text{ gal}) = \underline{27.78 \text{ mpg}}$

(b) $(3.785 \text{ L/gal}) / [(27.78 \text{ miles/gal})(1.609 \text{ km/mile})]$
 $= 0.0847 \text{ L/km} = \underline{8.47 \text{ L/100 km}}$

(c) rate of fuel use during trip
 $\dot{m}_f = [(18 \text{ gal})(3.785 \text{ L/gal})(0.692 \text{ kg/L})] / [(12.5 \text{ hr})(3600 \text{ sec/hr})]$
 $= 0.001048 \text{ kg/sec}$

mass of CO
 $(0.001048 \text{ kg/sec}) [(28 \text{ gm/kg})] (3600 \text{ sec/hr}) (12.5 \text{ hr}) / (1000 \text{ gm/kg})$
 $= \underline{1.32 \text{ kg}}$

(2-13)

(a) displacement volume of one cylinder

$$V_d = (0.0056 \text{ m}^3) / (10 \text{ cylinders}) = 0.00056 \text{ m}^3/\text{cylinder}$$

eq (2-8)

$$V_d = (\pi/4) B^2 S = (0.00056 \text{ m}^3) = (\pi/4) B^2 (1.12 \text{ B})$$

$$B = 0.0860 \text{ m} \quad S = 1.12 B = (1.12)(0.0860 \text{ m}) = 0.0963 \text{ m}$$

eq (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev}) (0.0963 \text{ m/stroke}) (3600/60 \text{ rev/sec})$$
$$= \underline{11.56 \text{ m/sec}}$$

(b) eq (2-76)

$$\tau = [(159.2)(162)] / (3600/60) = \underline{429.8 \text{ N-m}}$$

(c) eq (2-87)

$$b_{mep} = [(6.28)(2)(429.8)] / (5.6) = \underline{964 \text{ kPa}}$$

(2-14)

(a) displacement volume of one cylinder

$$V_d = (4800 \text{ cm}^3)/(8) = 600 \text{ cm}^3/\text{cylinder}$$

Eq. (2-8)

$$V_d = (\pi/4)B^2S = 600 \text{ cm}^3 = (\pi/4)(1.06 \text{ S})^2S$$

$$S = 8.79 \text{ cm} = 0.0879 \text{ m}$$

(b) Eq. (2-2)

$$\begin{aligned} \bar{U}_p &= 2SN = (2 \text{ strokes/rev})(0.0879 \text{ m/stroke})(2000/60 \text{ rev/sec}) \\ &= 5.86 \text{ m/sec} \end{aligned}$$

(c) each spark plug fires once each cycle

$$\begin{aligned} &(2000/2 \text{ cycles/min})(60 \text{ min/hr})(24 \text{ hr/day})(5 \text{ days}) \\ &= 7.20 \times 10^6 \text{ cycles} \end{aligned}$$

(d) Eq. (2-71)

$$\dot{m}_a = \eta_v \rho_a V_d N/n$$

$$\begin{aligned} &= (0.92)(1,181 \text{ kg/m}^3)(0.0048 \text{ m}^3/\text{cycle})(2000/60 \text{ rev/sec})/(2 \text{ rev/cycle}) \\ &= 0.0870 \text{ kg/sec} \end{aligned}$$

(e) Eq. (2-55)

$$\dot{m}_f = \dot{m}_a / AF = (0.0870 \text{ kg/sec})/(14.6) = 0.00595 \text{ kg/sec}$$

(2-15)

(a)

Eq. (2-8) with $B = S$

$$V_d = 6.28 \text{ cm}^3 = (\pi/4)B^2S = (\pi/4)B^3$$

$$B = 2.00 \text{ cm} = S$$

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.0200 \text{ m/stroke})(8000/60 \text{ rev/sec}) = \underline{5.33 \text{ m/sec}}$$

(b)

Eq. (2-71)

$$\dot{m}_s = \rho_s V_d \eta_r N/n = (1.181)(0.00000628)(0.85)(8000/60)/(1) = \underline{0.00084 \text{ kg/sec}}$$

(c)

Eq. (2-56)

$$\dot{m}_r = (FA)\dot{m}_s = (0.067)(0.00084 \text{ kg/sec}) = \underline{5.63 \times 10^{-5} \text{ kg/sec}}$$

(d)

$$m_r = (5.63 \times 10^{-5} \text{ kg/sec})/[8000/60 \text{ rev/sec}](1 \text{ cycle/rev}) = \underline{4.22 \times 10^{-7} \text{ kg/cycle}}$$

(2-16)

(a)

brake power using Eq. (2-43)

$$\dot{W}_b = 2\pi N\tau = (2\pi \text{ radians/rev})(800/60 \text{ rev/sec})(76 \text{ N-m})/(1000 \text{ W/kW}) = 6.365 \text{ kW}$$

or using Eq. (2-80)

$$\dot{W}_b = (800/60)(76)/159.2 = 6.365 \text{ kW}$$

mass flow rate of fuel

$$\dot{m}_f = (0.113/4 \text{ kg/min})(1000 \text{ gm/kg})(60 \text{ min/hr}) = 1695 \text{ gm/hr}$$

Eq. (2-60)

$$\text{bsfc} = \dot{m}_f/\dot{W}_b = (1695 \text{ gm/hr})/(6.365 \text{ kW}) = \underline{266.3 \text{ gm/kW-hr}}$$

(b)

displacement volume using Eq. (2-9)

$$V_d = N_c(\pi/4)B^2S = (1 \text{ cyl})(\pi/4)(12.9 \text{ cm})^2(18.0 \text{ cm}) \\ = 2353 \text{ cm}^3 = 2.353 \text{ L} = 0.002353 \text{ m}^3$$

Eq. (2-41)

$$\text{bmep} = 4\pi\tau/V_d = (4\pi)(76 \text{ N-m})/(0.002353 \text{ m}^3) = 405,700 \text{ N/m}^2 = \underline{405.7 \text{ kPa}}$$

or using Eq. (2-87)

$$\text{bmep} = (6.28)(2)(76)/(2.353) = \underline{405.7 \text{ kPa}}$$

or using Eq. (2-88)

$$\text{bmep} = (1000)(6.365)(2)/[(2.353)(800/60)] = \underline{405.7 \text{ kPa}}$$

(c)

$$\text{from above } \dot{W}_b = \underline{6.365 \text{ kW}}$$

(d)

piston face area using Eq. (2-15)

$$A_p = (\pi/4)B^2 = (\pi/4)(12.9 \text{ cm})^2 = 130.7 \text{ cm}^2$$

Eq. (2-51)

$$\text{SP} = \dot{W}_b/A_p = (6.365 \text{ kW})/(130.7 \text{ cm}^2) = \underline{0.0487 \text{ kW/cm}^2}$$

(e)

$$\text{Eq. (2-52)} \quad \text{OPD} = \dot{W}_b/V_d = (6.365 \text{ kW})/(2.353 \text{ L}) = \underline{2.71 \text{ kW/L}}$$

(f)

$$\text{Eq. (2-53)} \quad \text{SV} = V_d/\dot{W}_b = (2.353 \text{ L})/(6.365 \text{ kW}) = \underline{0.370 \text{ L/kW}}$$

(2-17)

(a) $\dot{Q} = \dot{m} c_p \Delta T$
 $[(72 \text{ hp})(2545 \text{ BTU/hr/hp})(0.93)]/(60 \text{ min/hr})$
 $= (30 \text{ gal/min})(62.4 \text{ lbm/ft}^3)(0.1337 \text{ ft}^3/\text{gal})(1 \text{ BTU/lbm}\cdot^\circ\text{R})\Delta T$
 $\Delta T = 11^\circ \text{ F} \quad T_{\text{exit}} = 46^\circ + 11^\circ = \underline{57^\circ \text{ F}}$

(b) Eq. (2-43)

$$\dot{W}_b = 2\pi N \tau = (72 \text{ hp})(550 \text{ ft-lbf/sec/hp})(60 \text{ sec/min}) = (2\pi \text{ radians/rev})(4050 \text{ rev/min})\tau$$
$$\tau = \underline{93.4 \text{ lbf-ft}}$$

or using Eq. (2-77)

$$\tau = (5252)(72)/(4050) = \underline{93.4 \text{ lbf-ft}}$$

(c) brake power $\dot{W}_b = (72 \text{ hp})(550 \text{ ft-lbf/sec/hp})(60 \text{ sec/min}) = 2.376 \times 10^6 \text{ ft-lbf/min}$

displacement $V_d = (302 \text{ in.}^3)/(12 \text{ in./ft})^3 = 0.1748 \text{ ft}^3$

Eq. (2-86)

$$\text{bmep} = n \dot{W}_b / V_d N = (2 \text{ rev/cycle})(2.376 \times 10^6 \text{ ft-lbf/min}) / (0.1748 \text{ ft}^3)(4050 \text{ rev/min})$$
$$= 6712.4 \text{ lbf/ft}^2 = \underline{46.6 \text{ psia}}$$

or using Eq. (2-90)

$$\text{bmep} = [(396,000)(72)(2)] / [(302)(4050)] = \underline{46.6 \text{ psia}}$$

(2-18)

(a) power out of generator

$$\dot{W}_g = (220 \text{ volts})(54.2 \text{ amps}) = 11,924 \text{ W} = 11.924 \text{ kW}$$

brake power from engine using Eq. (2-50)

$$\dot{W}_b = \dot{W}_g / \eta_{\text{gen}} = (11.924 \text{ kW}) / 0.87 = \underline{13.7 \text{ kW} = 18.4 \text{ hp}}$$

(b) Eq. (2-43)

$$\dot{W}_b = 2\pi N \tau = 13.7 \text{ kW} = (2\pi \text{ radians/rev})(1200/60 \text{ rev/sec})\tau$$
$$\tau = 0.109 \text{ kN-m} = \underline{109 \text{ N-m}}$$

or using Eq. (2-76)

$$\tau = (159.2)(13.7)/(1200/60) = \underline{109 \text{ N-m}}$$

(c) Eq. (2-40)

$$\tau = (\text{bmep})V_d/2\pi = 109 \text{ N-m} = (\text{bmep})(0.0031 \text{ m}^3/\text{rev})/(2\pi \text{ radians/rev})$$
$$\text{bmep} = 221,000 \text{ N/m}^2 = \underline{221 \text{ kPa}}$$

or using Eq. (2-87)

$$\text{bmep} = (6.28)(1)(109)/(3.1) = \underline{221 \text{ kPa}}$$

(2-19)

(a)

Eq. (2-55)

$$\dot{m}_a = \dot{m}_f(\text{AF}) = (0.198 \text{ kg/sec})(1.7) = 0.3366 \text{ kg/sec}$$

Eq. (2-71)

$$\eta_v = n\dot{m}_a / \rho_a V_d N = (2)(0.3366) / (1.181)(0.006)(6000/60) = 0.950 = \underline{95.0\%}$$

(b)

$$\dot{m}_a = \underline{0.3366 \text{ kg/sec}} \quad \text{from above}$$

(c)

Eq. (2-64) : heat in for engine per time

$$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (0.198 \text{ kg/sec})(10,920 \text{ kJ/kg})(0.99) = 2140.5 \text{ kJ/sec}$$

heat in for engine per cycle

$$Q_{in} = (2140.5 \text{ kJ/sec})(2 \text{ rev/cycle}) / (6000/60 \text{ rev/sec}) = 42.81 \text{ kJ/cycle}$$

heat in per cycle per cylinder

$$Q_{in} = (42.81 \text{ kJ/cycle}) / (8 \text{ cylinder}) = \underline{5.35 \text{ kJ/cyl-cycle}}$$

(d)

$$\dot{Q}_{unburned} = \dot{m}_f Q_{HV} (1 - \eta_c) = (0.198 \text{ kg/sec})(10,920 \text{ kJ/kg})(1 - 0.99) = \underline{21.6 \text{ kW}}$$

(2-20)

assuming four-stroke cycle

(a) Eq. (2-71)

$$\begin{aligned}\dot{m}_a &= \eta_v \rho_a V_d N / n \\ &= (0.51) (1.181 \text{ kg/m}^3) (0.0046 \text{ m}^3/\text{cycle}) (1750/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ &= \underline{0.0404 \text{ kg/sec}}\end{aligned}$$

(b) Eq. (2-55)

$$\dot{m}_f = \dot{m}_a / \text{AF} = (0.0404 \text{ kg/sec}) / (14.5) = \underline{0.00278 \text{ kg/sec}}$$

(c) Eq. (2-60)

$$\begin{aligned}\text{bsfc} = \dot{m}_f / \dot{W}_b &= [(0.00278 \text{ kg/sec}) (1000 \text{ gm/kg}) (3600 \text{ sec/hr})] / (32.4 \text{ kW}) \\ &= \underline{309 \text{ gm/kW-hr}}\end{aligned}$$

(d) with same indicated thermal efficiency and same combustion efficiency, fuel flow needed will be proportional to mechanical efficiency, fuel flow rate needed for V4:

$$\dot{m}_f = (0.00278 \text{ kg/sec}) [(75/87)] = 0.00240 \text{ kg/sec}$$

Eq. (2-55) gives air flow needed

$$\dot{m}_a = \dot{m}_f (\text{AF}) = (0.00240 \text{ kg/sec}) (18.2) = 0.0437 \text{ kg/sec}$$

use Eq. (2-71) to find needed engine speed

$$\begin{aligned}\dot{m}_a &= \eta_v \rho_a V_d N / n = (0.0437 \text{ kg/sec}) \\ &= (0.86) (1.181 \text{ kg/m}^3) (0.0023 \text{ m}^3/\text{cycle}) (N/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ &\underline{N = 2245 \text{ RPM}}\end{aligned}$$

(e) Eq. (2-60)

$$\begin{aligned}\text{bsfc} = \dot{m}_f / \dot{W}_b &= [(0.00240 \text{ kg/sec}) (1000 \text{ gm/kg}) (3600 \text{ sec/hr})] / (32.4 \text{ kW}) \\ &= \underline{267 \text{ gm/kW-hr}}\end{aligned}$$

(2-21)

$$(a) V_1 = (70 \text{ MPH}) / (2.237 \text{ MPH/m/sec}) = 31.29 \text{ m/sec}$$

$$V_2 = (20) / (2.237) = 8.94 \text{ m/sec}$$

$$\begin{aligned}\Delta KE &= (m/2g_c) [V_1^2 - V_2^2] \\ &= (1900 \text{ kg}) / [(2) (1 \text{ kg-m/N-sec}^2)] [(31.29 \text{ m/sec})^2 - (8.94)^2] = 854,180 \text{ N-m} \\ &= \underline{854.18 \text{ kJ}}\end{aligned}$$

51% of this is recovered in battery

$$E = (854.18 \text{ kJ}) (0.51) = \underline{436 \text{ kJ}}$$

(b) 24% of chemical energy recovered

$$e = (26950 \text{ kJ/kg}) (0.24) = 6468 \text{ kJ/kg}$$

mass of fuel saved

$$m = (436 \text{ kJ}) / (6468 \text{ kJ/kg}) = \underline{0.067 \text{ kg}}$$

CHAPTER 3

(3-1)

(a)(b) using Fig. 3-2

$$\begin{aligned} T_1 &= 60^\circ \text{C} = 333 \text{ K} && \text{given} \\ P_1 &= 98 \text{ kPa} && \text{given} \end{aligned}$$

Eqs. (3-4) and (3-5)

$$\begin{aligned} T_2 &= T_1(r_c)^{k-1} = (333 \text{ K})(9.5)^{0.35} = 732 \text{ K} = 459^\circ \text{C} \\ P_2 &= P_1(r_c)^k = (98 \text{ kPa})(9.5)^{1.35} = 2047 \text{ kPa} \end{aligned}$$

Eq. (3-11)

$$\begin{aligned} Q_{\text{HV}}\eta_c &= (AF + 1)c_v(T_3 - T_2) \\ (43,000 \text{ kJ/kg})(0.96) &= (15.5 + 1)(0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 732 \text{ K}) \\ T_3 &= 3779 \text{ K} = 3506^\circ \text{C} \end{aligned}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (2047 \text{ kPa})(3779/732) = 10,568 \text{ kPa}$$

Eqs. (3-16) and (3-17)

$$\begin{aligned} T_4 &= T_3(1/r_c)^{k-1} = (3779 \text{ K})(1/9.5)^{0.35} = 1719 \text{ K} = 1446^\circ \text{C} \\ P_4 &= P_3(1/r_c)^k = (10,568 \text{ kPa})(1/9.5)^{1.35} = 506 \text{ kPa} \end{aligned}$$

(c)

Eq. (3-18)

$$w_{3-4} = R(T_4 - T_3)/(1 - k) = (0.287 \text{ kJ/kg}\cdot\text{K})(1719 - 3779)\text{K}/(1 - 1.35) = 1689 \text{ kJ/kg}$$

(d)

Eq. (3-12)

$$q_{\text{in}} = c_v(T_3 - T_2) = (0.821 \text{ kJ/kg}\cdot\text{K})(3779 - 732)\text{K} = 2502 \text{ kJ/kg}$$

(e)

Eq. (3-7)

$$w_{1-2} = R(T_2 - T_1)/(1 - k) = (0.287 \text{ kJ/kg}\cdot\text{K})(732 - 333)\text{K}/(1 - 1.35) = -327 \text{ kJ/kg}$$

$$w_{\text{net}} = w_{1-2} + w_{3-4} = (-327 \text{ kJ/kg}) + (+1689 \text{ kJ/kg}) = +1362 \text{ kJ/kg}$$

(f)

$$\eta_t = w_{\text{net}}/q_{\text{in}} = 1362/2502 = 0.545 = 54.5\%$$

or using Eqs. (3-29) or (3-31)

$$\eta_t = 1 - (T_1/T_2) = 1 - (333/732) = 0.545$$

$$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/9.5)^{0.35} = 0.545 = 54.5\%$$

(3-2)

(a) using Fig. 3-2

$$\text{for 1 cylinder} \quad V_d = (3 \text{ L})/6 = 0.5 \text{ L} = 0.0005 \text{ m}^3$$

Eq. (2-12)

$$r_c = 9.5 = (V_d + V_c)/V_c = (0.0005 + V_c)/V_c \quad V_c = 0.0000588 \text{ m}^3$$
$$V_1 = V_{\text{BDC}} = V_d + V_c = 0.0005 + 0.0000588 = 0.0005588 \text{ m}^3$$

mass in cylinder at point 1

$$m = PV/RT = (98 \text{ kPa})(0.0005588 \text{ m}^3)/(0.287 \text{ kJ/kg}\cdot\text{K})(333 \text{ K}) = 0.000573 \text{ kg}$$

$$\text{work per cylinder per cycle} \quad W = mw_{\text{net}} = (0.000573 \text{ kg})(1362 \text{ kJ/kg}) = 0.780 \text{ kJ}$$

Eq. (2-42)

$$\dot{W}_1 = WN/n$$
$$= [(0.780 \text{ kJ/cycle})(2400/60 \text{ rev/sec}) / (2 \text{ rev/cycle})] (6 \text{ cyl}) = 93.6 \text{ kW}$$

Eq. (2-47)

$$\dot{W}_b = \eta_m \dot{W}_1 = (0.84)(93.6 \text{ kW}) = \underline{78.6 \text{ kW}}$$

(b) Eq. (2-43)

$$\dot{W}_b = 2\pi N\tau = 78.6 \text{ kJ/sec} = (2\pi \text{ radians/rev})(2400/60 \text{ rev/sec})\tau$$
$$\tau = 0.313 \text{ kN}\cdot\text{m} = \underline{313 \text{ N}\cdot\text{m}}$$

(c) Eq. (2-41)

$$\tau = (\text{bmep})V_d/4\pi = 0.313 \text{ kN}\cdot\text{m} = \text{bmep}(0.003 \text{ m}^3)/4\pi \quad \text{bmep} = \underline{1311 \text{ kPa}}$$

(d) Eq. (2-49)

$$\dot{W}_r = \dot{W}_1 - \dot{W}_b = (93.6 \text{ kW}) - (78.6 \text{ kW}) = \underline{15.0 \text{ kW}}$$

(e) for 1 cylinder from (a) above

$$m_m = 0.000573 \text{ kg} = m_a + m_r = m_a(1 + \text{FA}) = m_a[1 + (1/15.5)]$$
$$m_a = 0.000538 \text{ kg} \quad m_r = 0.000035 \text{ kg}$$

$$\dot{m}_r = (0.000035 \text{ kg/cycle-cyl})(6 \text{ cyl})(2400/60 \text{ rev/sec})/(2 \text{ rev/cycle})$$
$$= 0.0042 \text{ kg/sec} = 4.2 \text{ gm/sec} = 15,120 \text{ gm/hr}$$

Eq. (2-60)

$$\text{bsfc} = \dot{m}_r/\dot{W}_b = (15,120 \text{ gm/hr})/(78.6 \text{ kW}) = \underline{192.4 \text{ gm/kW}\cdot\text{hr}}$$

(f) Eq. (2-70)

$$\eta_v = m_a/\rho_a V_d = [(0.000538 \text{ kg})/(1.181 \text{ kg/m}^3)(0.0005 \text{ m}^3)](100) = \underline{91.1\%}$$

(g) Eq. (2-52)

$$\text{OPD} = \dot{W}_b/V_d = (78.6 \text{ kW})/(3 \text{ L}) = \underline{26.2 \text{ kW/L}}$$

(3-3)

(a)

using Fig. 3-6

Eq. (3-37)

$$T_7 = T_{ex} = T_4(P_{ex}/P_4)^{(k-1)/k} \\ = (1719 \text{ K})(100/506)^{(1.35-1)/1.35} = 1129 \text{ K} = \underline{856^\circ \text{ C}}$$

(b)

Eq. (3-46)

$$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9.5)(1719/1129)(100/506) = 0.032 = \underline{3.2\%}$$

(c)

Eq. (3-50)

$$(T_m)_1 = x_r T_{ex} + (1 - x_r) T_a$$

$$333 \text{ K} = (0.032)(1129) + (1 - 0.032)T_a$$

$$T_a = 307 \text{ K} = \underline{34^\circ \text{ C}}$$

(3-4)

(a)

using Fig. 3-4

expansion cooling of exhaust residual when intake valve opens

$$T_{ex} = (1129 \text{ K})(75/100)^{(1.35-1)/1.35} = 1048 \text{ K}$$

Eq. (3-50)

$$T_1 = x_r T_{ex} + (1 - x_r) T_a \\ = (0.032)(1048 \text{ K}) + (1 - 0.032)(307 \text{ K}) = 331 \text{ K} = \underline{58^\circ \text{ C}}$$

(b)

Eq. (3-4)

$$T_2 = T_1(r_c)^{k-1} = (331 \text{ K})(9.5)^{0.35} = 728 \text{ K} = \underline{455^\circ \text{ C}}$$

(3-5)

(a)(b)

using Fig. 3-2

$$\begin{array}{ll} T_1 = 100^\circ \text{ F} = 560^\circ \text{ R} & \text{given} \\ P_1 = 14.7 \text{ psia} & \text{given} \end{array}$$

Eqs. (3-4) and (3-5)

$$\begin{array}{l} T_2 = T_1(r_c)^{k-1} = (560^\circ \text{ R})(10)^{1.4-1} = 1407^\circ \text{ R} = 947^\circ \text{ F} \\ P_2 = P_1(r_c)^k = (14.7 \text{ psia})(10)^{1.4} = 369 \text{ psia} \end{array}$$

Eq. (3-12)

$$q_{in} = c_v(T_3 - T_2) = 800 \text{ BTU/lbm} = (0.216 \text{ BTU/lbm}\cdot^\circ\text{R})(T_3 - 1407^\circ \text{ R})$$

$$T_3 = 5110^\circ \text{ R} = 4650^\circ \text{ F}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (369 \text{ psia})(5110/1407) = 1340 \text{ psia}$$

Eqs. (3-16) and (3-17)

$$\begin{array}{l} T_4 = T_3(1/r_c)^{k-1} = (5110^\circ \text{ R})(1/10)^{1.3-1} = 2561^\circ \text{ R} = 2101^\circ \text{ F} \\ P_4 = P_3(1/r_c)^k = (1340 \text{ psia})(1/10)^{1.3} = 67.2 \text{ psia} \end{array}$$

(c)

Eq. (3-7)

$$\begin{aligned} w_{1-2} &= R(T_2 - T_1)/(1 - k) \\ &= [(0.069 \text{ BTU/lbm}\cdot^\circ\text{R})(1407 - 560)^\circ\text{R}]/(1 - 1.4) = -146.1 \text{ BTU/lbm} \end{aligned}$$

Eq. (3-18)

$$\begin{aligned} w_{3-4} &= R(T_4 - T_3)/(1 - k) \\ &= [(0.069 \text{ BTU/lbm}\cdot^\circ\text{R})(2561 - 5110)^\circ\text{R}]/(1 - 1.3) = +586.3 \text{ BTU/lbm} \end{aligned}$$

$$\eta_t = w_{net}/q_{in} = [(+586.3) + (-146.1)]/(800) = 0.550 = 55.0\%$$

Eq. (3-31)

$$\eta_t = 0.550 = 1 - (1/r_c)^{k-1} = 1 - (1/10)^{k-1}$$

$$\underline{k = 1.347}$$

(3-6)

(a)(b)

using Fig. 3-8

$$T_1 = 65^\circ \text{C} = 338 \text{ K} \quad \text{given}$$

$$P_1 = 130 \text{ kPa} \quad \text{given}$$

Eqs. (3-52) and (3-53)

$$T_2 = T_1(r_c)^{k-1} = (338 \text{ K})(19)^{0.35} = 947 \text{ K} = 674^\circ \text{C}$$

$$P_2 = P_1(r_c)^k = (130 \text{ kPa})(19)^{1.35} = 6922 \text{ kPa}$$

use Eq. (2-57) for actual air-fuel ratio

$$\text{AF} = (\text{AF})_{\text{stoich}}/\phi = (14.5)/(0.8) = 18.125$$

Eq. (3-58)

$$Q_{\text{HV}}\eta_c = (\text{AF} + 1)c_p(T_3 - T_2)$$

$$(42,500 \text{ kJ/kg})(0.98) = (18.125 + 1)(1.108 \text{ kJ/kg}\cdot\text{K})(T_3 - 947)\text{K}$$

$$T_3 = 2913 \text{ K} = 2640^\circ \text{C}$$

$$P_3 = P_2 = 6922 \text{ kPa}$$

$$v_4 = v_1 = RT_1/P_1 = (0.287)(338)/(130) = 0.7462 \text{ m}^3/\text{kg}$$

$$v_3 = RT_3/P_3 = (0.287)(2913)/(6922) = 0.1208 \text{ m}^3/\text{kg}$$

Eqs. (3-64) and (3-65)

$$T_4 = T_3(v_3/v_4)^{k-1} = (2913 \text{ K})(0.1208/0.7462)^{0.35} = 1540 \text{ K} = 1267^\circ \text{C}$$

$$P_4 = P_3(v_3/v_4)^k = (6922 \text{ kPa})(0.1208/0.7462)^{1.35} = 592 \text{ kPa}$$

(c)

Eq. (3-62)

$$\beta = T_3/T_2 = 2913/947 = 3.08$$

(d)

Eq. (3-73)

$$(\eta)_\text{DIESEL} = 1 - (1/r_c)^{k-1}[(\beta^k - 1)/\{k(\beta - 1)\}]$$

$$\eta_t = 1 - (1/19)^{0.35}[\{(3.08)^{1.35} - 1\}/\{(1.35)(3.08 - 1)\}] = 0.547 = 54.7\%$$

(e)

Eq. (3-59)

$$q_{\text{in}} = c_p(T_3 - T_2) = (1.108 \text{ kJ/kg}\cdot\text{K})(2913 - 947)\text{K} = 2178 \text{ kJ/kg}$$

$$w_{\text{net}} = q_{\text{in}}\eta_t = (2178 \text{ kJ/kg})(0.547) = 1191 \text{ kJ/kg}$$

$$q_{\text{ex}} = q_{\text{out}} = q_{\text{in}} - w_{\text{net}} = 2178 - 1191 = 987 \text{ kJ/kg}$$

(3-7) using Fig.3-11

$$T_1 = 50^\circ \text{C} = 323 \text{ K} \quad \text{given}$$

$$P_1 = 98 \text{ kPa} \quad \text{given}$$

Eq. (3-52) and (3-53)

$$T_2 = T_1(r_c)^{k-1} = (323 \text{ K})(18)^{0.35} = 888 \text{ K} = 615^\circ \text{C}$$

$$P_2 = P_1(r_c)^k = (98 \text{ kPa})(18)^{1.35} = 4851 \text{ kPa}$$

$$P_3 = P_{\max} = 9000 \text{ kPa} = P_x$$

- (a) highest possible thermal efficiency will be when as much of combustion as possible is done at constant volume, i.e., as close to Otto cycle as possible

$$\text{at constant volume } T_x = T_2(P_3/P_2) = (888 \text{ K})(9000/4851) = 1647 \text{ K}$$

$$(AF) = 1/(FA) = 1/0.054 = 18.52$$

total heat in is found by combining Eqs. (3-76), (3-81), and (3-86)

$$(Q_{in})_{total} = Q_{2-x} + Q_{x-3} = m_f Q_{HV} \eta_c = (m_a + m_p) c_v (T_x - T_1) + (m_a + m_p) c_p (T_3 - T_x)$$

let $\eta_c = 1$ and divide by m_f

$$Q_{HV} = (AF + 1) c_v (T_x - T_1) + (AF + 1) c_p (T_3 - T_x)$$

$$42,500 \text{ kJ/kg} = 19.52(0.821 \text{ kJ/kg}\cdot\text{K})(1647 - 888) \text{ K} + (19.52)(1.108 \text{ kJ/kg}\cdot\text{K})(T_3 - 1647) \text{ K}$$

$$T_3 = 3050 \text{ K}$$

pressure ratio using Eq. (3-79)

$$\alpha = P_x/P_2 = 9000/4851 = 1.855$$

cutoff ratio using Eq. (3-85)

$$\beta = T_3/T_x = 3050/1647 = 1.852$$

thermal efficiency using Eq. (3-89)

$$(\eta)_{DUAL} = 1 - (1/r_c)^{k-1} [\{\alpha\beta^k - 1\} / \{k\alpha(\beta - 1) + \alpha - 1\}]$$

$$= 1 - (1/18)^{0.35} [\{(1.855)(1.852)^{1.35} - 1\} / \{(1.35)(1.855)(1.852 - 1) + 1.855 - 1\}] = 0.603 = \underline{60.3\%}$$

- (b) $T_{\text{peak}} = T_3 = 3050 \text{ K} = \underline{2777^\circ \text{C}}$ from above

- (c) minimum thermal efficiency is when combustion is at constant pressure, i.e., operate as a Diesel cycle

Eq. (3-58)

$$Q_{HV} \eta_c = (AF + 1) c_p (T_3 - T_2) = (42,500 \text{ kJ/kg})(1) = (18.52 + 1)(1.108 \text{ kJ/kg}\cdot\text{K})(T_3 - 888 \text{ K})$$

$$T_3 = 2853 \text{ K}$$

cutoff ratio using Eq. (3-62)

$$\beta = T_3/T_2 = 2853/888 = 3.213$$

thermal efficiency using Eq. (3-73)

$$(\eta)_{DIESEL} = 1 - (1/r_c)^{k-1} [(\beta^k - 1) / \{k(\beta - 1)\}]$$

$$= 1 - (1/18)^{0.35} [\{(3.213)^{1.35} - 1\} / \{1.35(3.213 - 1)\}] = 0.533 = \underline{53.3\%}$$

- (d) $T_{\text{peak}} = T_3 = 2853 \text{ K} = \underline{2580^\circ \text{C}}$ from above

(3-8)

(a) (b) using Fig. 3-11

$$T_1 = 60^\circ \text{C} = 333 \text{ K} \quad \text{given}$$

$$P_1 = 101 \text{ kPa} \quad \text{given}$$

Eqs. (3-52) and (3-53)

$$T_2 = T_1(r_2)^{k-1} = (333 \text{ K})(14)^{0.35} = 839 \text{ K} = 566^\circ \text{C}$$

$$P_2 = P_1(r_2)^k = (101 \text{ kPa})(14)^{1.35} = 3561 \text{ kPa}$$

Eq. (3-11) with half of heat in at constant volume

$$Q_{\text{in}}\eta_c = (AF + 1)c_v(T_x - T_2)$$

$$\frac{1}{2}(42,500 \text{ kJ/kg})(1) = (20 + 1)(0.821 \text{ kJ/kg}\cdot\text{K})(T_x - 839 \text{ K})$$

$$T_x = 2072 \text{ K} = 1799^\circ \text{C}$$

Eq. (3-58) with half of heat in at constant pressure

$$Q_{\text{in}}\eta_c = (AF + 1)c_p(T_3 - T_x)$$

$$\frac{1}{2}(42,500 \text{ kJ/kg})(1) = (20 + 1)(1.108 \text{ kJ/kg}\cdot\text{K})(T_3 - 2072 \text{ K})$$

$$T_3 = 2985 \text{ K} = 2712^\circ \text{C}$$

Eq. (3-78)

$$P_x = P_2(T_x/T_2) = (3561 \text{ kPa})(2072/839) = 8794 \text{ kPa} = P_3$$

$$v_4 = v_1 = RT_1/P_1 = (0.287)(333)/(101) = 0.9462 \text{ m}^3/\text{kg}$$

$$v_3 = RT_3/P_3 = (0.287)(2985)/(8794) = 0.0974 \text{ m}^3/\text{kg}$$

Eqs. (3-64) and (3-65)

$$T_4 = T_3(v_3/v_4)^{k-1} = (2985 \text{ K})(0.0974/0.9462)^{0.35} = 1347 \text{ K} = 1074^\circ \text{C}$$

$$P_4 = P_3(v_3/v_4)^k = (8794 \text{ kPa})(0.0974/0.9462)^{1.35} = 408 \text{ kPa}$$

(c) Eq. (3-85)

$$\beta = T_3/T_x = 2985/2072 = 1.441$$

(d) Eq. (3-79)

$$\alpha = P_3/P_2 = 8794/3561 = 2.470$$

(e) Eq. (3-89)

$$(\eta)_{\text{DUAL}} = 1 - (1/r_2)^{k-1} [\{\alpha\beta^k - 1\} / \{k\alpha(\beta - 1) + \alpha - 1\}]$$

$$\eta_t = 1 - (1/14)^{0.35} \{[(2.470)(1.441)^{1.35} - 1] / [(1.35)(2.470)(0.441) + 2.470 - 1]\} = 0.589 = 58.9\%$$

(f) Eq. (3-87)

$$q_{\text{in}} = c_v(T_x - T_2) + c_p(T_3 - T_x)$$

$$= (0.821 \text{ kJ/kg}\cdot\text{K})(2072 - 839) \text{ K} + ((1.108 \text{ kJ/kg}\cdot\text{K})(2985 - 2072) \text{ K}) = 2024 \text{ kJ/kg}$$

$$(g) w_{\text{net}} = \eta_t q_{\text{in}} = (0.589)(2024 \text{ kJ/kg}) = 1192 \text{ kJ/kg}$$

(3-9)

(a)

using Fig.3-11

Eq. (2-43)

$$\dot{W} = 2\pi N\tau = 57 \text{ kJ/sec} = (2\pi \text{ radians/rev})(2000/60 \text{ rev/sec})\tau$$
$$\tau = 0.272 \text{ kN-m} = \underline{272 \text{ N-m}}$$

(b)

for 1 cylinder

$$V_d = (0.0033 \text{ m}^3)/6 = 0.00055 \text{ m}^3$$

Eq. (2-12) $r_c = (V_d + V_c)/V_c = 14 = (0.00055 + V_c)/V_c$

$$V_c = 0.000042 \text{ m}^3$$

$$V_1 = V_d + V_c = (0.00055 \text{ m}^3) + (0.000042 \text{ m}^3) = 0.000592 \text{ m}^3$$

mass in 1 cylinder

$$m_1 = P_1 V_1 / RT_1 = (101)(0.000592)/(0.287)(333) = 0.000626 \text{ kg}$$

using q_{in} and η_i values from Problem 3-8

$$Q_{in} = m q_{in} = (0.000626 \text{ kg})(2024 \text{ kJ/kg})(6 \text{ cyl}) = 7.602 \text{ kJ/cycle}$$

$$(W_p)_{net} = \eta_i Q_{in} = (0.589)(7.602 \text{ kJ/cycle}) = 4.48 \text{ kJ/cycle}$$

Eq. (2-42)

$$\dot{W}_i = WN/n = (4.48 \text{ kJ/cycle})(2000/60 \text{ rev/sec})/(2 \text{ rev/cycle}) = 74.7 \text{ kW}$$

Eq. (2-47) $\eta_m = \dot{W}_b/\dot{W}_i = 57/74.7 = 0.763 = \underline{76.3\%}$

(c)

Eq. (2-41)

$$\tau = (bmep)V_d/4\pi = 272 \text{ N-m} = bmep(0.0033 \text{ m}^3)/4\pi \quad \underline{bmep = 1036 \text{ kPa}}$$

(d)

with AF = 20, mass of fuel will be (1/21) of total mass

$$m_f = (0.000626 \text{ kg/cyl-cycle})(1/21)(6 \text{ cyl}) = 0.00018 \text{ kg/cycle}$$

$$\dot{m}_f = (0.00018 \text{ kg/cycle})(2000/60 \text{ rev/sec})/(2 \text{ rev/cycle})$$
$$= 0.003 \text{ kg/sec} = 10.8 \text{ kg/hr} = 10,800 \text{ gm/hr}$$

Eq. (2-60)

$$bsfc = \dot{m}_f/\dot{W}_b = (10,800 \text{ gm/hr})/(57 \text{ kW}) = \underline{189 \text{ gm/kW-hr}}$$

(3-10)

(a)

using Eq. (3-37) and Fig. 3-6

$$T_{ex} = T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2800 \text{ K})(100/9000)^{(1.35-1)/1.35} \\ = 872 \text{ K} = \underline{599^\circ \text{C}}$$

(b)

Eq. (3-1h)

$$T_4 = T_3(P_4/P_3)^{(k-1)/k} = (2800 \text{ K})(460/9000)^{(1.35-1)/1.35} = 1295 \text{ K}$$

Eq. (3-46)

$$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9)(1295/872)(100/460) = 0.036 = \underline{3.6\%}$$

(c)

velocity will be sonic - choked flow

Eq. (3-1j)

$$\text{Vel} = c = [kRT]^{1/2} = [(1.35)(287 \text{ J/kg-K})(1295 \text{ K})]^{1/2} = \underline{708 \text{ m/sec}}$$

(d)

as velocity is dissipated kinetic energy will be changed to an enthalpy increase

$$V^2/2g_c = \Delta h = c_p \Delta T$$

$$(708 \text{ m/sec})^2 / [(2)(1 \text{ kg-m/N-sec}^2)] = (1.108 \text{ kJ/kg-K}) \Delta T$$

$$\Delta T = 226^\circ \text{K}$$

$$T_{\max} = T_7 + \Delta T = 872 + 226 = 1098 \text{ K} = \underline{825^\circ \text{C}}$$

(3-11)

(a)(b)

using Fig. 3-5

$$T_1 = 70^\circ \text{C} = 343 \text{ K} \quad \text{given}$$

$$P_1 = 140 \text{ kPa} \quad \text{given}$$

Eqs. (3-4) and (3-5)

$$T_2 = T_1(r_c)^{k-1} = (343 \text{ K})(8)^{0.35} = 710 \text{ K} = 437^\circ \text{C}$$

$$P_2 = P_1(r_c)^k = (140 \text{ kPa})(8)^{1.35} = 2319 \text{ kPa}$$

Eq. (3-12)

$$q_{in} = c_v(T_3 - T_2) = 1800 \text{ kJ/kg} = (0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 710)\text{K}$$

$$T_3 = 2902 \text{ K} = 2629^\circ \text{C}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (2319 \text{ kPa})(2902/710) = 9479 \text{ kPa}$$

Eqs. (3-16) and (3-17)

$$T_4 = T_3(1/r_c)^{k-1} = (2902 \text{ K})(1/8)^{0.35} = 1402 \text{ K} = 1129^\circ \text{C}$$

$$P_4 = P_3(1/r_c)^k = (9479 \text{ kPa})(1/8)^{1.35} = 572 \text{ kPa}$$

(c)

Eq. (3-18)

$$\begin{aligned} w_{3-4} &= R(T_4 - T_3)/(1 - k) \\ &= [(0.287 \text{ kJ/kg}\cdot\text{K})(1402 - 2902)\text{K}]/(1 - 1.35) = +1230 \text{ kJ/kg} \end{aligned}$$

(d)

Eq. (3-7)

$$\begin{aligned} w_{1-2} &= R(T_2 - T_1)/(1 - k) \\ &= [(0.287 \text{ kJ/kg}\cdot\text{K})(710 - 343)\text{K}]/(1 - 1.35) = -301 \text{ kJ/kg} \end{aligned}$$

(e)

$$v_1 = RT_1/P_1 = (0.287)(343)/(140) = 0.7032 \text{ m}^3/\text{kg}$$

$$v_2 = RT_2/P_2 = (0.287)(710)/(2319) = 0.0879 \text{ m}^3/\text{kg}$$

using Eq. (3-35) per unit mass

$$\begin{aligned} w_{\text{pump}} &= (P_1 - P_{\text{ex}})(v_1 - v_2) \\ &= [(140 - 100)\text{kPa}][(0.7032 - 0.0879)\text{m}^3/\text{kg}] = 24.6 \text{ kJ/kg} \end{aligned}$$

(f)

$$w_{\text{net}} = (-301) + (+1230) + (+24.6) = 953.6 \text{ kJ/kg}$$

$$\eta_t = w_{\text{net}}/q_{in} = 953.6/1800 = 0.530 = 53.0\%$$

(3-12)

(a)(b)

using Fig. 3-15

$$T_7 = T_8 = 70^\circ \text{C} = 343 \text{ K} \quad \text{given}$$

$$P_7 = P_8 = 140 \text{ kPa} \quad \text{given}$$

$$T_2 = T_7(r_c)^{k-1} = (343 \text{ K})(8)^{0.35} = 710 \text{ K} = 437^\circ \text{C}$$

$$P_2 = P_7(r_c)^k = (140 \text{ kPa})(8)^{1.35} = 2319 \text{ kPa}$$

$$q_{in} = c_v(T_3 - T_2) = 1800 \text{ kJ/kg} = (0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 710)\text{K}$$

$$T_3 = 2902 \text{ K} = 2629^\circ \text{C}$$

$$\text{at constant volume } P_3 = P_2(T_3/T_2) = (2319 \text{ kPa})(2902/710) = 9479 \text{ kPa}$$

$$T_4 = T_3(1/r_c)^{k-1} = (2902 \text{ K})(1/10)^{0.35} = 1296 \text{ K} = 1023^\circ \text{C}$$

$$P_4 = P_3(1/r_c)^k = (9479 \text{ kPa})(1/10)^{1.35} = 423 \text{ kPa}$$

$$\text{at constant volume } T_5 = T_4(P_5/P_4) = (1296 \text{ K})(100/423) = 306 \text{ K} = 33^\circ \text{C} = T_6$$

$$P_5 = P_6 = 100 \text{ kPa} \quad \text{given}$$

(c)

Eq. (3-1i)

$$w_{3-4} = R(T_4 - T_3)/(1 - k) = (0.287 \text{ kJ/kg}\cdot\text{K})(1296 - 2902)\text{K}/(1 - 1.35) = +1317 \text{ kJ/kg}$$

(d)

Eq. (3-1i)

$$w_{7-2} = (0.287 \text{ kJ/kg}\cdot\text{K})(710 - 343)\text{K}/(1 - 1.35) = -301 \text{ kJ/kg}$$

(e)

$$v_5 = RT_5/P_5 = (0.287)(306)/(100) = 0.8790 \text{ m}^3/\text{kg}$$

$$v_7 = RT_7/P_7 = (0.287)(343)/(140) = 0.7032 \text{ m}^3/\text{kg}$$

$$v_6 = v_7/r_c = 0.7032/8 = 0.0879 \text{ m}^3/\text{kg}$$

$$w_{5-6} = P(v_6 - v_5) = (100)(0.0879 - 0.8790) = -79.1 \text{ kJ/kg}$$

$$w_{6-7} = P(v_7 - v_6) = (140)(0.7032 - 0.0879) = +86.1 \text{ kJ/kg}$$

$$w_{7-8} \text{ cancels } w_{8-7}$$

$$w_{\text{pump}} = (+86.1) + (-79.1) = +7.0 \text{ kJ/kg}$$

(f)

$$w_{\text{net}} = (+1317) + (-301) + (+7.0) = +1023 \text{ kJ/kg}$$

$$\eta_t = w_{\text{net}}/q_{in} = 1023/1800 = 0.568 = 56.8\%$$

(3-13)

(a)(b)

using Fig. 3-16

$$T_7 = 70^\circ \text{C} = 343 \text{ K} \quad P_7 = 140 \text{ kPa} \quad \text{given}$$

$$T_2 = T_7(r_c)^{k-1} = (343 \text{ K})(8)^{0.35} = 710 \text{ K} = 437^\circ \text{C}$$

$$P_2 = P_7(r_c)^k = (140 \text{ kPa})(8)^{1.35} = 2319 \text{ kPa}$$

$$q_{in} = c_v(T_3 - T_2) = 1800 \text{ kJ/kg} = (0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 710)\text{K}$$
$$T_3 = 2902 \text{ K} = 2629^\circ \text{C}$$

$$\text{at constant volume} \quad P_3 = P_2(T_3/T_2) = (2319 \text{ kPa})(2902/710) = 9479 \text{ kPa}$$

$$T_4 = T_3(1/r_c)^{k-1} = (2902 \text{ K})(1/10)^{0.35} = 1296 \text{ K} = 1023^\circ \text{C}$$

$$P_4 = P_3(1/r_c)^k = (9479 \text{ kPa})(1/10)^{1.35} = 423 \text{ kPa}$$

$$P_5 = 100 \text{ kPa} = P_6 \quad \text{given}$$

$$\text{at constant volume} \quad T_5 = T_4(P_5/P_4) = (1296 \text{ K})(100/423) = 306 \text{ K} = 33^\circ \text{C} = T_6$$

$$v_1 = v_5 = v_4 = RT_5/P_5 = (0.287 \text{ kJ/kg}\cdot\text{K})(306 \text{ K})/(100 \text{ kPa}) = 0.8790 \text{ m}^3/\text{kg}$$

$$v_6 = v_3 = v_2 = v_5/r_c = (0.8790 \text{ m}^3/\text{kg})/10 = 0.0879 \text{ m}^3/\text{kg}$$

$$v_7 = RT_7/P_7 = (0.287)(343)/(140) = 0.7032 \text{ m}^3/\text{kg}$$

$$P_1 = P_7(v_7/v_1)^k = (140 \text{ kPa})(0.7032/0.8790)^{1.35} = 104 \text{ kPa}$$

$$T_1 = P_1 v_1/R = (104 \text{ kPa})(0.8790 \text{ m}^3/\text{kg})/(0.287 \text{ kJ/kg}\cdot\text{K}) = 318 \text{ K} = 45^\circ \text{C}$$

(c)

Eq. (3-1i)

$$w_{3-4} = R(T_4 - T_3)/(1 - k) = (0.287 \text{ kJ/kg}\cdot\text{K})(1296 - 2902)\text{K}/(1 - 1.35) = +1317 \text{ kJ/kg}$$

(d)

Eq. (3-1i)

$$w_{7-2} = (0.287 \text{ kJ/kg}\cdot\text{K})(710 - 343)\text{K}/(1 - 1.35) = -301 \text{ kJ/kg}$$

(e)

$$w_{6-7} = P(v_7 - v_6) = (140)(0.7032 - 0.0879) = +86.1 \text{ kJ/kg}$$

$$w_{5-6} = P(v_6 - v_5) = (100)(0.0879 - 0.8790) = -79.1 \text{ kJ/kg}$$

$$w_{7-1} \text{ cancels } w_{1-7}$$

$$w_{\text{pump}} = (+86.1) + (-79.1) = +7.0 \text{ kJ/kg}$$

(f)

$$w_{\text{net}} = (+1317) + (-301) + (+7.0) = +1023 \text{ kJ/kg}$$

$$\eta_t = w_{\text{net}}/q_{in} = 1023/1800 = 0.568 = 56.8\%$$

(3-14)

(a) Eq. (3-4)

$$T_2 = T_1(r_c)^{k-1} = (570^\circ\text{R})(10.5)^{1.35-1} = \underline{1298^\circ\text{R} = 838^\circ\text{F}}$$

(b) $R = r/a = (6.64 \text{ in.})/(1.66 \text{ in.}) = 4.0$

Eq. (2-14) gives chamber volume when intake valve closes

$$V_1/V_c = 1 + \frac{1}{2}(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$$

$$= (1) + (\frac{1}{2})(10.5-1)[(4.0)+(1)-\cos(200^\circ)-\sqrt{(4.0)^2-\sin^2(200^\circ)}] = 10.283$$

Eq. (2-14) for volume when spark plug fires

$$V_2/V_c = (1) + (\frac{1}{2})(10.5-1)[(4.0)+(1)-\cos(245^\circ)-\sqrt{(4.0)^2-\sin^2(245^\circ)}]$$

$$= 1.202$$

$$V_1/V_2 = (V_1/V_c)/(V_2/V_c) = (10.283)/(1.202) = 8.556$$

$$T_2 = T_1(V_1/V_2)^{k-1} = (570^\circ\text{R})(8.556)^{1.35-1} = \underline{1208^\circ\text{R} = 748^\circ\text{F}}$$

(3-15)

(a) $P_2 = P_7(r_c)^k = (100 \text{ kPa})(8.2)^{1.35} = 1713 \text{ kPa}$

$$P_{\text{min}} = P_1(1/r_c)^k = (1713 \text{ kPa})(1/10.2)^{1.35} = \underline{74.5 \text{ kPa}}$$

(b) Miller cycle has no pump work $\underline{W_{\text{pump}} = 0}$

(c) $P_{\text{EVO}} = P_4 = P_3(1/r_c)^k = (9197 \text{ kPa})(1/10.2)^{1.35} = \underline{400 \text{ kPa}}$

(3-16)

(a) $R = r/a = (9.5 \text{ in.})/(2.5 \text{ in.}) = 3.8$

Eq. (2-14)

$$V_2/V_1 = V_2/V_c = 1 + \frac{1}{2}(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$$

$$= (1) + (\frac{1}{2})(10.5-1)[(3.8)+(1)-\cos(110^\circ)-\sqrt{(3.8)^2-\sin^2(110^\circ)}] = 7.935$$

$$T_2 = T_1(V_1/V_2)^{k-1} = (4660^\circ\text{R})(1/7.935)^{1.35-1} = \underline{2257^\circ\text{R} = 1797^\circ\text{F}}$$

(b) $\underline{(r_c)_{\text{eff}} = 7.935}$

(c) $P_7 = P_6[(r_c)_{\text{eff}}]^k = (17.8 \text{ psia})(7.935)^{1.35} = 292 \text{ psia}$

at constant volume

$$T_7 = T_1(P_7/P_1) = (4660^\circ\text{R})(292/1137) = \underline{1197^\circ\text{R} = 737^\circ\text{F}}$$

(3-17)

(a)

Eq. (2-43)

$$\dot{W}_b = 2\pi N\tau = 3600 \text{ kJ/sec} = (2\pi \text{ radians/rev})(210/60 \text{ rev/sec})\tau$$
$$\tau = 164 \text{ kN-m} = 164,000 \text{ N-m}$$

(b)

Eq. (2-9)

$$V_d = N_c(\pi/4)B^2S = (6 \text{ cyl})(\pi/4)(0.35 \text{ m})^2(1.05 \text{ m}) = 0.606 \text{ m}^3 = 606 \text{ L}$$

(c)

Eq. (2-40)

$$\tau = (\text{bmep})V_d/2\pi = 164 \text{ kN-m} = \text{bmep}(0.606 \text{ m}^3)/2\pi$$
$$\text{bmep} = 1700 \text{ kPa}$$

(d)

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(1.05 \text{ m/stroke})(210/60 \text{ rev/sec}) = 7.35 \text{ m/sec}$$

(3-18)

(a)

Eq. (2-60)

$$\text{bsfc} = \dot{m}_f/\dot{W}_b = (31.7 \text{ gm/min})(60 \text{ min/hr})/(1.42 \text{ kW}) = 1339 \text{ gm/kW-hr}$$

(b)

Eq. (2-9) with $S = B$

$$V_d = N_c(\pi/4)B^2S = (1 \text{ cyl})(\pi/4)B^2S = (1)(\pi/4)B^3 = 7.54 \text{ cm}^3$$
$$B = S = 2.13 \text{ cm} = 0.0213 \text{ m}$$

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.0213 \text{ m/stroke})(23,000/60 \text{ rev/sec}) = 16.33 \text{ m/sec}$$

(c)

65% gets trapped, so 35% gets exhausted
in addition only 94% of trapped fuel gets burned

$$\dot{m}_{ex} = (0.35)(31.7 \text{ gm/min}) + (1 - 0.94)(0.65)(31.7 \text{ gm/min}) = 12.3 \text{ gm/min}$$

(d)

Eq. (2-43)

$$\dot{W}_b = 2\pi N\tau = 1.42 \text{ kJ/sec} = (2\pi \text{ radians/rev})(23,000/60 \text{ rev/sec})\tau$$
$$\tau = 0.00059 \text{ kN-m} = 0.59 \text{ N-m}$$

(3-19)

(a)(b)

using Fig. 3-21

$$T_1 = T_2 = 70^\circ \text{ F} = 530^\circ \text{ R} \quad \text{given}$$

$$P_1 = P_2 = P_0 = 14.7 \text{ psia} \quad \text{given}$$

$$V_2 = (\pi/4)B^2(S/2) = (\pi/4)(1 \text{ ft})^2(3 \text{ ft}/2) = 1.178 \text{ ft}^3$$

mass of air-fuel in cylinder

$$m_2 = P_2 V_2 / RT_2 = [(14.7)(144) \text{ lbf/ft}^2](1.178 \text{ ft}^3) / [(53.33 \text{ ft-lbf/lbm} \cdot ^\circ \text{R})(530^\circ \text{ R})] \\ = 0.0882 \text{ lbm}$$

with AF = 18, then mass of fuel will be

$$m_f = (0.0882 \text{ lbm})(1/19) = 0.00464 \text{ lbm}$$

Eq. (3-11) assuming combustion efficiency = 100%

$$Q_{\text{HV}} \eta_c = (AF + 1) c_v (T_3 - T_2)$$

$$(12,000 \text{ BTU/lbm})(1) = (18 + 1)(0.196 \text{ BTU/lbm} \cdot ^\circ \text{R})(T_3 - 530^\circ \text{ R})$$

$$T_3 = 3752^\circ \text{ R} = \underline{3292^\circ \text{ F}}$$

at constant volume

$$P_3 = P_2 (T_3/T_2) = (14.7 \text{ psia})(3752/530) = \underline{104 \text{ psia}}$$

Eqs. (3-124) and (3-125) with $v_4 = 2v_3$

$$T_4 = T_3 (v_3/v_4)^{k-1} = (3752^\circ \text{ R})(1/2)^{0.35} = 2944^\circ \text{ R} = \underline{2484^\circ \text{ F}}$$

$$P_4 = P_3 (v_3/v_4)^k = (104 \text{ psia})(1/2)^{1.35} = \underline{40.8 \text{ psia}}$$

$$P_5 = \underline{14.7 \text{ psia}}$$

at constant volume

$$T_5 = T_4 (P_5/P_4) = (2944^\circ \text{ R})(14.7/40.8) = 1061^\circ \text{ R} = \underline{601^\circ \text{ F}}$$

(c)

Eq. (3-133)

$$\eta_c = 1 - [(T_4 - T_2) + k(T_5 - T_2)] / (T_3 - T_2)$$

$$= 1 - [(2944 - 1061)^\circ \text{R} + 1.35(1061 - 530)^\circ \text{R}] / (3752 - 530)^\circ \text{R}$$

$$= 0.193 = \underline{19.3\%}$$

(d)

for one cycle for 1 side of piston

Eq. (3-126)

$$W_{3-4} = mc_v(T_3 - T_4) = (0.0882 \text{ lbm})(0.196 \text{ BTU/lbm}\cdot^\circ\text{R})(3752 - 2944)^\circ\text{R} = 13.97 \text{ BTU}$$

Eq. (3-131)

$$W_{3-2} = P_0(V_2 - V_3) = [(14.7)(144) \text{ lbf/ft}^2][(\pi/4)(1 \text{ ft})^2(-1.5 \text{ ft})]/(778 \text{ ft}\cdot\text{lbf/BTU}) \\ = -3.21 \text{ BTU}$$

W_{1-2} cancels W_{2-1}

$$W_{\text{net}} = (13.97 \text{ BTU}) + (-3.21 \text{ BTU}) = 10.76 \text{ BTU}$$

indicated power at 140 RPM using Eq. (2-42)

$$\dot{W}_i = WN/n = [(10.76 \text{ BTU/cycle})(140/60 \text{ rev/sec})/(1 \text{ rev/cycle})](3600 \text{ sec/hr}) \\ = 90,384 \text{ BTU/hr} = (90,384 \text{ BTU/hr})/(2545 \text{ BTU/hr/hp}) = 35.51 \text{ hp}$$

$$\text{Eq. (2-47)} \quad \dot{W}_b = \dot{W}_i \eta_m = (35.51 \text{ hp})(0.05) = 1.78 \text{ hp}$$

$$\text{using both sides of piston} \quad \dot{W}_b = (2)(1.78 \text{ hp}) = \underline{3.56 \text{ hp}}$$

(e)

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(3 \text{ ft/stroke})(140/60 \text{ rev/sec}) = \underline{14 \text{ ft/sec}}$$

(3-20)

(a)

using Fig. 3-2

$$\underline{T_1 = 27^\circ \text{C} = 300 \text{ K}} \quad \underline{P_1 = 100 \text{ kPa}} \quad \text{given}$$

Eqs. (3-4) and (3-5)

$$T_2 = T_1(r_c)^{k-1} = (300 \text{ K})(8)^{0.35} = 621 \text{ K} = \underline{348^\circ \text{C}}$$

$$P_2 = P_1(r_c)^k = (100 \text{ kPa})(8)^{1.35} = \underline{1656 \text{ kPa}}$$

Eq. (3-12)

$$q_{\text{in}} = c_v(T_3 - T_2) = 2000 \text{ kJ/kg} = (0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 621)\text{K} \\ T_3 = 3057 \text{ K} = \underline{2784^\circ \text{C}}$$

$$\text{at constant volume } P_3 = P_2(T_3/T_2) = (1656 \text{ kPa})(3057/621) = \underline{8152 \text{ kPa}}$$

Eqs. (3-16) and (3-17)

$$T_4 = T_3(1/r_c)^{k-1} = (3057 \text{ K})(1/8)^{0.35} = 1476 \text{ K} = \underline{1203^\circ \text{C}}$$

$$P_4 = P_3(1/r_c)^k = (8152 \text{ kPa})(1/8)^{1.35} = \underline{492 \text{ kPa}}$$

(b)

Eq. (3-31)

$$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/8)^{0.35} = 0.517 = \underline{51.7\%}$$

(c)

using air tables from Ref. [73]

$$\underline{T_1 = 27^\circ \text{C} = 300 \text{ K}} \quad \underline{P_1 = 100 \text{ kPa}} \quad \text{given}$$

$$v_1 = v_4 = RT_1/P_1 = (0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K})/(100 \text{ kPa}) = 0.861 \text{ m}^3/\text{kg}$$

Eq. (2-12)

$$v_2 = v_1/r_c = (0.861 \text{ m}^3/\text{kg})/8 = 0.1076 \text{ m}^3/\text{kg} = v_3$$

for isentropic compression using relative specific volumes

$$(v_2/v_1) = (v_{r2}/v_{r1}) = (1/8) = v_{r2}/62.393 \quad v_{r2} = 7.799$$

$$\underline{T_2 = 673 \text{ K} = 400^\circ \text{C}} \quad \text{from tables}$$

$$P_2 = RT_2/v_2 = (0.287)(673)/(0.1076) = \underline{1795 \text{ kPa}}$$

$$u_2 = 491.41 \text{ kJ/kg} \quad \text{from tables}$$

$$q = (u_3 - u_2) = 2000 \text{ kJ/kg} = (u_3 - 491.41 \text{ kJ/kg})$$

$$u_3 = 2491.41 \text{ kJ/kg} \quad T_3 = 2829 \text{ K} = \underline{2556^\circ \text{C}} \quad \text{from tables}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (1795 \text{ kPa})(2829/673) = \underline{7545 \text{ kPa}}$$

for isentropic expansion using relative specific volumes

$$v_{r4} = v_{r3}(v_4/v_3) = (0.08548)(8) = 0.68384$$

$$\underline{T_4 = 1524 \text{ K} = 1251^\circ \text{C}} \quad \text{from tables}$$

$$P_4 = RT_4/v_4 = (0.287)(1524)/(0.861) = \underline{508 \text{ kPa}}$$

(d)

Eq. (3-7) using internal energy values from tables

$$w_{1-2} = (u_1 - u_2) = 214.32 - 491.41 = -277.09 \text{ kJ/kg}$$

Eq. (3-18)

$$w_{3-4} = (u_3 - u_4) = 2491.41 - 1227.32 = 1264.09 \text{ kJ/kg}$$

$$w_{\text{net}} = (1264.09 \text{ kJ/kg}) + (-277.09 \text{ kJ/kg}) = +987.00 \text{ kJ/kg}$$

thermal efficiency

$$\eta_t = w_{\text{net}}/q_{\text{in}} = 987.00/2000 = 0.494 = \underline{49.4\%}$$

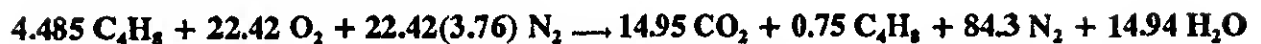
CHAPTER 4

- (4-1) an unknown amount of fuel burned with an unknown amount of air with z = amount of water removed before analysis

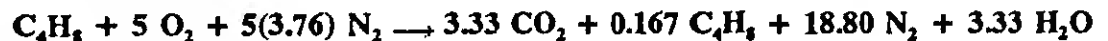


conservation of N	$y(3.76) = 84.3$	$y = 22.42$
conservation of O	$2(22.42) = 2(14.95) + z$	$z = 14.94$
conservation of H	$8x = 8(0.75) + 2(14.94)$	$x = 4.485$

put these into reaction equation



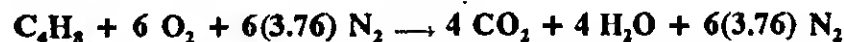
divide by 4.485



- (a) Eqs. (2-55) and (4-1)

$$\text{AF} = m_a/m_f = N_a M_a / N_f M_f = [5(4.76)(29)] / [(1)(56)] = \underline{12.325}$$

- (b) stoichiometric reaction equation



$$\text{stoichiometric air-fuel ratio} \quad (\text{AF})_{\text{stoch}} = [6(4.76)(29)] / [(1)(56)] = 14.79$$

$$\text{Eq. (4-2)} \quad \phi = (\text{AF})_{\text{stoch}} / (\text{AF})_{\text{act}} = 14.79 / 12.325 = \underline{1.20}$$

- (c) Eq. (4-6)

$$Q_{\text{LHV}} = Q_{\text{HHV}} - \Delta h_{\text{vap}} \quad (\text{evaporation of water in products})$$

for 1 kgmole of fuel in stoichiometric reaction there are 4 kgmoles of water

for 1 mole of fuel (h_g value at 25° C from Ref. [90])

$$\Delta h_{\text{vap}} = (4 \text{ kgmoles})(18 \text{ kg/kgmole})(2442.3 \text{ kJ/kg}) = 175.85 \text{ MJ}$$

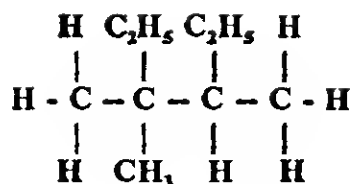
$$\text{for 1 kg of fuel} \quad \Delta h_{\text{vap}} = (175.85 \text{ MJ}) / 56 = 3.1 \text{ MJ}$$

$$Q_{\text{LHV}} = Q_{\text{HHV}} - \Delta h_{\text{vap}} = (46.9 \text{ MJ/kg}) - (3.1 \text{ MJ/kg}) = \underline{43.8 \text{ MJ/kg}}$$

- (d) Eq. (2-63)

$$Q_{\text{in}} = m_f Q_{\text{LHV}} \eta_c = (1 \text{ kg})(43.8 \text{ MJ/kg})(0.98) = \underline{42.9 \text{ MJ}}$$

(4-2)

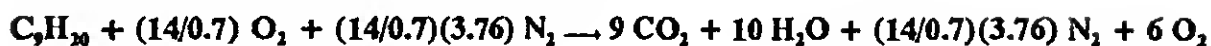


Paraffin Family

stoichiometric chemical reaction



reaction with equivalence ratio $\phi = 0.7$



this reduces to

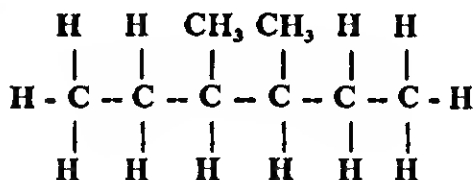


Eqs. (2-55) and (4-1)

$$\text{AF} = m_a/m_f = N_a M_a / N_f M_f = [(14)(4.76)(29)] / [(1)(128)] = \underline{15.10}$$

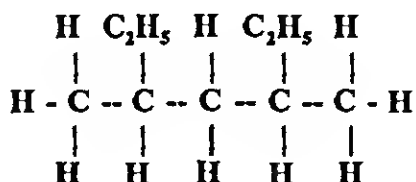
(4-3)

(a)



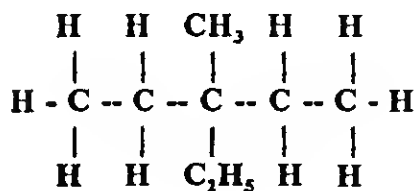
isomer of octane

(b)



isomer of nonane

(c)



isomer of octane

(4-4)

chemical reaction equation



(a) Eqs. (2-56) and (4-1)

$$\text{FA} = m_f/m_a = N_f M_f / N_a M_a = [(1)(2)] / [(0.5)(32)] = \underline{0.125}$$

(b) stoichiometric $\phi = 1$

(c) (using enthalpy values for water from Introduction to Thermodynamics, by Sonntag and Van Wylen, 3rd ed., John Wiley and Sons, 1991)

Eqs. (4-5) and (4-8)

$$\sum_{\text{PROD}} N_i (h_i^\circ + \Delta h)_i = \sum_{\text{REACT}} N_i (h_i^\circ + \Delta h)_i$$

$$(1)[(-241,826) + \Delta h]_{\text{H}_2\text{O}} = (1)[0 + 0]_{\text{H}_2} + (\frac{1}{2})[0 + 0]_{\text{O}_2}$$

$$\Delta h_{\text{H}_2\text{O}} = 241,826 \text{ kJ/kgmoie} \quad \underline{T_{\text{max}} = 4991 \text{ K}}$$

(d) exhaust is all H_2O with $P_{\text{H}_2\text{O}} = P_{\text{ex}} = 101 \text{ kPa}$

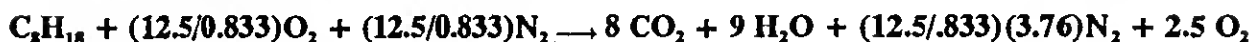
$$\underline{T_{\text{DP}} = 100^\circ \text{ C}}$$

(4-5)

stoichiometric combustion equation



at equivalence ratio $\phi = 0.833$



this reduces to



(a) Eqs. (2-55) and (4-1)

$$\text{AF} = m_a/m_f = N_a M_a / N_f M_f = [(15)(4.76)(29)] / [(1)(114)] = \underline{18.16}$$

(b) amount of air relative to stoichiometric

$$\% \text{ air} = [(15)(4.76)] / [(12.5)(4.76)] = 1.20 = 120\% \text{ air} = \underline{20\% \text{ excess air}}$$

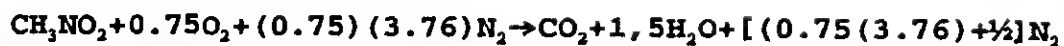
(c) Eq. (4-9) and values from Table A-2

$$\text{AKI} = (\text{MON} + \text{RON})/2 = (100 + 100)/2 = \underline{100}$$

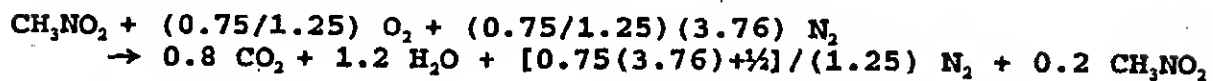
$$\text{Eq. (4-10) and values from Table A-2} \quad \text{FS} = \text{RON} - \text{MON} = 100 - 100 = \underline{0}$$

(4-6)

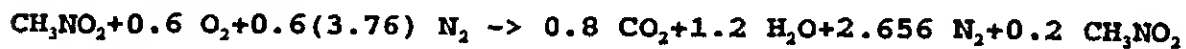
stoichiometric combustion



at equivalence ratio $\phi = 1.25$



this reduces to



(a)

$$\% \text{ air} = [(0.6)(4.76)]/[(0.75)(4.76)] = 0.80 = \underline{80\% \text{ stoichiometric air}}$$

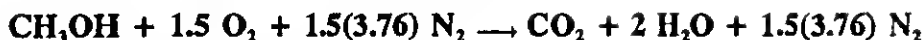
(b)

Eqs. (2-55) and (4-1)

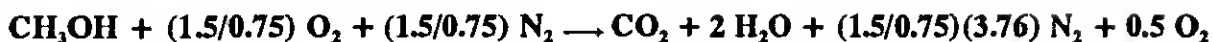
$$\text{AF} = m_a/m_f = N_a M_a / N_f M_f = [(0.6)(4.76)(29)]/[(1)(61)] = \underline{1.36}$$

(4-7)

stoichiometric combustion reaction



at equivalence ratio $\phi = 0.75$



this reduces to



(a) Eqs. (2-55) and (4-1)

$$\text{AF} = m_a/m_f = N_a M_a / N_f M_f = [2(4.76)(29)] / [(1)(32)] = \underline{8.63}$$

(b) mole fraction of water $x = N_{\text{water}}/N_{\text{total}} = 2/[1 + 2 + 2(3.76) + 0.5] = 0.1815$

vapor pressure of water $P_v = xP_{\text{total}} = (0.1815)(101 \text{ kPa}) = 18.33 \text{ kPa}$

using steam tables from Ref. [90] $T_{\text{DP}} = \underline{58^\circ \text{C}}$

(c) using psychrometric equations and steam tables from Ref. [90]

$$P_v = (\text{rh})P_s = (0.40)(3.169 \text{ kPa}) = 1.268 \text{ kPa}$$

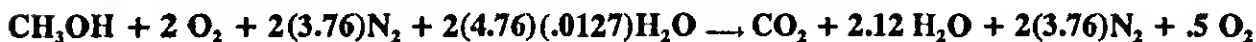
specific humidity

$$\omega = 0.622[P_v/(P_{\text{total}} - P_v)] = (0.622)[1.268/(101 - 1.268)] = 0.0079 \text{ kg}_v/\text{kg}_a$$

convert this to molar units using Eq. (4-1)

$$\omega = (0.0079)(29/18) = 0.0127 \text{ moles}_v/\text{moles}_a$$

adding this amount of water vapor to the inlet reactants



mole fraction of water $x = 2.12/[1 + 2.12 + 2(3.76) + 0.5] = 0.190$

vapor pressure of water $P_v = (0.190)(101 \text{ kPa}) = 19.22 \text{ kPa}$

from steam tables $T_{\text{DP}} = \underline{59^\circ \text{C}}$

(d) Eq. (4-9)

$$\text{AKI} = (\text{MON} + \text{RON})/2 = (92 + 106)/2 = \underline{99}$$

(4-8) thermal efficiency using Eq. (3-31)

$$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/8.5)^{0.35} = 0.527$$

for 1 cylinder $V_d = (3 \text{ L})/4 = 0.75 \text{ L} = 0.00075 \text{ m}^3$

Eq. (2-12)

$$r_c = (V_d + V_c)/V_c = 8.5 = (0.00075 + V_c)/V_c \quad V_c = 0.0001 \text{ m}^3$$

Eq. (2-11) $V_{\text{BDC}} = V_d + V_c = (0.00075 \text{ m}^3) + (0.0001 \text{ m}^3) = 0.00085 \text{ m}^3$

mass in cylinder evaluated at BDC after intake

$$m = PV/RT = (100 \text{ kPa})(0.00085 \text{ m}^3)/(0.287 \text{ kJ/kg}\cdot\text{K})(333 \text{ K}) = .00089 \text{ kg} = m_a + m_f$$

for 1 cycle using gasoline with AF = 14.6 $m_f = (0.00089 \text{ kg})/15.6 = 0.000057 \text{ kg}$

Eq. (2-63)

$$\dot{Q}_{\text{in}} = m_f \dot{Q}_{\text{HV}} \eta_c = (0.000057 \text{ kg})(43,000 \text{ kJ/kg})(0.98) = 2.402 \text{ kJ/cyl-cycle}$$

rate of heat in

$$\dot{\dot{Q}}_{\text{in}} = (2.402 \text{ kJ/cyl-cycle})(4800/60 \text{ rev/sec})(4 \text{ cyl})/(2 \text{ rev/cycle}) = 384.3 \text{ kW}$$

Eq. (2-65) $\dot{W}_t = \dot{Q}_{\text{in}} \eta_t = (384.3 \text{ kW})(0.527) = \underline{203 \text{ kW}}$ using gasoline

for 1 cycle using methanol with AF = 6.5 $m_f = (0.00089 \text{ kg})/7.5 = 0.000119 \text{ kg}$

$$\dot{Q}_{\text{in}} = (0.000119 \text{ kg})(20,050 \text{ kJ/kg})(0.98) = 2.338 \text{ kJ/cyl-cycle}$$

rate of heat in

$$\dot{\dot{Q}}_{\text{in}} = (2.338 \text{ kJ/cyl-cycle})(4800/60 \text{ rev/sec})(4 \text{ cyl})/(2 \text{ rev/cycle}) = 374.1 \text{ kW}$$

$$\dot{W}_t = (374.1 \text{ kW})(0.527) = \underline{197 \text{ kW}}$$
 using methanol

fuel rate in for gasoline

$$\begin{aligned} \dot{m}_f &= (0.000057 \text{ kg/cyl-cycle})(4800/60 \text{ rev/sec})(4 \text{ cyl})/(2 \text{ rev/cycle}) \\ &= 0.00912 \text{ kg/sec} = 9.12 \text{ gm/sec} = 32,832 \text{ gm/hr} \end{aligned}$$

Eq. (2-61)

$$\text{isfc} = \dot{m}_f / \dot{W}_t = (32,832 \text{ gm/hr})/(203 \text{ kW}) = \underline{161.7 \text{ gm/kW-hr}}$$
 with gasoline

fuel rate in for methanol

$$\begin{aligned} \dot{m}_f &= (0.000119 \text{ kg/cyl-cycle})(4800/60 \text{ rev/sec})(4 \text{ cyl})/(2 \text{ rev/cycle}) \\ &= 0.01904 \text{ kg/sec} = 19.04 \text{ gm/sec} = 68,544 \text{ gm/hr} \end{aligned}$$

$$\text{isfc} = (68,544 \text{ gm/hr})/(197 \text{ kW}) = \underline{347.9 \text{ gm/kW-hr}}$$
 with methanol

(4-9)

stoichiometric combustion equation



(a) Eq. (2-57) and stoichiometric value from Table A-2

$$(\text{AF})_{\text{act}} = (\text{AF})_{\text{stoich}}/\phi = 9.0/1.10 = \underline{8.18}$$

(b) using Fig. 3-2 and Eqs. (3-4) and (3-5) for conditions at end of compression

$$T_2 = T_1(r_c)^{k-1} = (333 \text{ K})(10)^{0.35} = 745 \text{ K}$$

$$P_2 = P_1(r_c)^k = (101 \text{ kPa})(10)^{1.35} = 2261 \text{ kPa}$$

Eq. (3-11)

$$Q_{\text{HV}}\eta_c = (\text{AF} + 1)c_v(T_3 - T_2)$$

$$(26,950 \text{ kJ/kg})(0.97) = (8.18 + 1)(0.821 \text{ kJ/kg}\cdot\text{K})(T_3 - 745 \text{ K})$$

$$T_3 = T_{\text{peak}} = 4214 \text{ K} = \underline{3941^\circ \text{C}}$$

(c) at constant volume

$$P_3 = P_{\text{peak}} = P_2(T_3/T_2) = (2261 \text{ kPa})(4214/745) = \underline{12,789 \text{ kPa}}$$

(4-10)

(a) at stoichiometric $\phi = 1$

(b) actual AF will be stoichiometric value for isooctane from Table A-2

$$(\text{AF})_{\text{act}} = 15.1$$

stoichiometric AF for ethanol

$$(\text{AF})_{\text{stoich}} = 9.0$$

Eq. (2-57)

$$\phi = (\text{AF})_{\text{stoich}}/(\text{AF})_{\text{act}} = 9.0/15.1 = \underline{0.596}$$

(c) Eqs. (2-62), (2-64) and (2-65)

$$\dot{Q}_{\text{in}} = \dot{m}_f Q_{\text{HV}}\eta_c \quad \dot{W}_i = \eta_i \dot{Q}_{\text{in}} \quad \dot{W}_b = \eta_m \dot{W}_i$$

If the air flow rate is the same and the fuel injectors are not readjusted, then the fuel flow rate will be the same

for same η_v , η_c , η_m , \dot{m}_a , and \dot{m}_f

$$\begin{aligned} \frac{(\dot{W}_b)_{\text{ethanol}}}{(\dot{W}_b)_{\text{isooctane}}} &= \frac{(\dot{m}_f Q_{\text{HV}}\eta_c\eta_i\eta_m)_{\text{ethanol}}}{(\dot{m}_f Q_{\text{HV}}\eta_c\eta_i\eta_m)_{\text{isooctane}}} \\ &= \frac{(Q_{\text{HV}})_{\text{ethanol}}}{(Q_{\text{HV}})_{\text{isooctane}}} = (26,950 \text{ kJ/kg})/(44,300 \text{ kJ/kg}) = 0.608 \end{aligned}$$

there will be a 39.2% decrease in brake power with ethanol

(4-11)

for same thermal efficiency $\dot{W}_{out} \propto \dot{Q}_{in}$

(Eqs. (2-56) and (2-63))

$$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (FA)_{stoich} \dot{m}_a Q_{HV} \eta_c$$

using values from Table A-2

$$\begin{aligned} \dot{W}_{nitro} / \dot{W}_{gasoline} &= [(FA) \dot{m}_a Q_{HV} \eta_c]_{nitro} / [(FA) \dot{m}_a Q_{HV} \eta_c]_{gasoline} \\ &= [(FA) Q_{HV}]_{nitro} / [(FA) Q_{HV}]_{gasoline} \\ &= [(0.588)(10,920)] / [(0.068)(43,000)] = 2.20 = 220\% \end{aligned}$$

120% increase in power with nitromethane

(4-12)

for same thermal efficiency $\dot{W}_{out} \propto \dot{Q}_{in}$

Eqs. (2-56) and (2-64))

$$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (FA)_{stoich} \dot{m}_a Q_{HV} \eta_c$$

using values from Table A-2

$$\begin{aligned} \dot{W}_{methanol} / \dot{W}_{gasoline} &= [(FA) \dot{m}_a Q_{HV} \eta_c]_{methanol} / [(FA) \dot{m}_a Q_{HV} \eta_c]_{gasoline} \\ &= [(FA) Q_{HV}]_{methanol} / [(FA) Q_{HV}]_{gasoline} \\ &= [(0.155)(20,050)] / [(0.068)(43,000)] = 1.06 \end{aligned}$$

$$\begin{aligned} \dot{W}_{nitro} / \dot{W}_{gasoline} &= [(FA) \dot{m}_a Q_{HV} \eta_c]_{nitro} / [(FA) \dot{m}_a Q_{HV} \eta_c]_{gasoline} \\ &= [(FA) Q_{HV}]_{nitro} / [(FA) Q_{HV}]_{gasoline} \\ &= [(0.588)(10,920)] / [(0.068)(43,000)] = 2.20 \end{aligned}$$

(4-13)

using values from Table A-2

(a)

Eq. (4-9)

$$AKI = (MON + RON)/2 = (92 + 113)/2 = \underline{102.5}$$

(b)

using Fig. 4-7, 0.2 gm/L raises ON about 4

$$MON = 92 + 4 = \underline{96}$$

(c) mass of isodecane

$$m = (10 \text{ gal})(3.785 \text{ L/gal})(0.001 \text{ m}^3/\text{L})(768 \text{ kg/m}^3) = 29.07 \text{ kg}$$

Eq. (2-11) with x = mass of butene-1 needed

$$(x + 29.07)(87) = x(80) + (29.07)(92) \quad x = 20.764 \text{ kg}$$

gallons of butene-1 needed

$$(20.764 \text{ kg}) / [(595 \text{ kg/m}^3)(0.001 \text{ m}^3/\text{L})(3.785 \text{ L/gal})] = \underline{9.22 \text{ gal}}$$

(4-14)

(a)

use Eq. (2-55) to find mass flow rate of air into engine

$$\dot{m}_a = (AF)\dot{m}_f = (1.7)(0.198 \text{ kg/sec}) = 0.3366 \text{ kg/sec}$$

Eq. (2-71)

$$\eta_v = n\dot{m}_a / \rho_a V_d N$$

$$(2)(0.3366)/(1.181)(0.006)(6000/60) = 0.950 = \underline{95.0\%}$$

(b)

$$\dot{m}_a = \underline{0.3366 \text{ kg/sec}} \quad \text{from above}$$

(c)

fuel into 1 cylinder per cycle

$$m_f = [(0.198 \text{ kg/sec})(2 \text{ rev/cycle})]/[(6000/60 \text{ rev/sec})(8 \text{ cyl})] \\ = 0.000495 \text{ kg/cyl-cycle}$$

using Eq. (2-63) and heating value from Table A-2

$$Q_{in} = m_f Q_{HV} \eta_c = (0.000495 \text{ kg})(10,920 \text{ kJ/kg})(0.99) = \underline{5.35 \text{ kJ}}$$

(d)

unburned fuel

$$\dot{m}_f = (0.198 \text{ kg/sec})(1 - \eta_c) = (0.198)(0.01) = 0.00198 \text{ kg/sec}$$

$$\dot{Q}_{exhaust} = (0.00198 \text{ kg/sec})(10,920 \text{ kJ/kg}) = \underline{21.6 \text{ kW}}$$

(4-15)

(a)

Good alternate fuel:

- can be obtained from many sources
- decrease in some emissions
- high octane number
- high h_u which results in cooler engine cycle

(b)

Poor alternate fuel:

- low energy content - about twice as much fuel needed
- high aldehyde emissions
- corrosive to many materials
- poor starting characteristics

(4-16)

(a)

using Table A-3 and method from Ref. [90]

$$\log_{10} K_p = -0.913 \quad K_p = \underline{0.1222}$$

(b)

stoichiometric reaction equation



because N and O combine 1 to 1 there will be equal amounts of N_2 and O_2 at equilibrium and the actual reaction will be:



Eq. (4-4)

$$K_p = \frac{(N_C^{v_C} N_D^{v_D}) / (N_A^{v_A} N_B^{v_B}) (P/N_{\text{tot}})^{\Delta v}} = 0.1222 = [x/y^{1/2} y^{1/2}] [50 / (x+2y)]^{1-1/2-1/2} = x/y$$

$$\text{conservation of nitrogen} \quad 1 = x + 2y \quad x = 1 - 2y$$

$$0.1222 = (1 - 2y)/y \quad y = 0.4712 \quad x = 1 - 2y = 0.0576$$

$$\text{moles of NO at equilibrium } N_{\text{NO}} = \underline{0.0576}$$

(c)

$$\text{moles of O}_2 \text{ at equilibrium } N_{\text{O}_2} = \underline{0.4712}$$

(d)

equilibrium is independent of pressure because pressure term in equilibrium equation is equal to 1

$$\text{moles of NO at equilibrium } N_{\text{NO}} = \underline{0.0576}$$

(e)

actual reaction equation



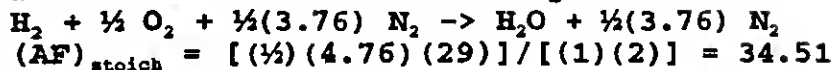
$$K_p = 0.1222 = [x(1)/y^{1/2} y^{1/2}(1)] [50 / (x+2y+1)]^{1+1-1/2-1/2-1} = x/y$$

the argon coefficients cancel and because the pressure term equals 1, neither the presence of argon nor the high pressure affect final equilibrium

$$\text{moles of NO at equilibrium } N_{\text{NO}} = \underline{0.0576}$$

(4-17)

(a) stoichiometric combustion equation



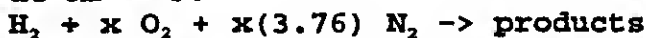
Eq. (2-57)

$$\phi = (\text{AF})_{\text{stoich}} / (\text{AF})_{\text{act}} = (34.51) / (30) = \underline{1.15}$$

(b) Eq. (2-58)

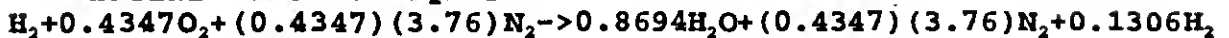
$$\lambda = 1/\phi = (1)/(1.15) = \underline{0.869}$$

(c) at $\text{AF} = 30$



$$\text{AF} = [x(4.76)(29)] / [(1)(2)] = 30 \quad x = 0.4347$$

actual reaction equation

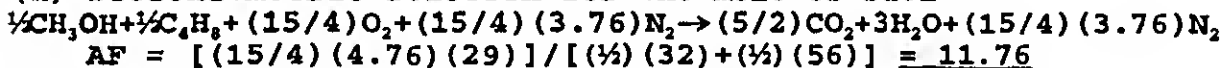


Eq. (4-5) with enthalpy values from reference [90]

$$Q = \sum_{\text{PROD}} N_i h_i - \sum_{\text{REACT}} N_i h_i$$
$$= (0.8694)[(-241,826) - (0)] + (0.4347)(3.76)[(0) + (0)]$$
$$+ (0.1306)[(0) + (0)] - (1)[(0) + (0)] - (0.4347)[(0) + (0)]$$
$$- (0.4347)(3.76)[(0) + (0)] = \underline{210,244 \text{ kJ}}$$

(4-18)

(a) stoichiometric reaction for one mole of fuel



(b) find mass percents

$$\text{methanol } m = (\frac{1}{2})(32) = 16 \text{ kg} \quad \text{mass \% } (16/44) = 0.364$$
$$\text{butene-1 } m = (\frac{1}{2})(56) = \underline{28 \text{ kg}} \quad (28/44) = 0.636$$
$$44 \text{ kg}$$

Eq. (4-11)

$$\text{ON} = (\% \text{ of A})(\text{ON}_A) + (\% \text{ of B})(\text{ON}_B)$$

$$\text{RON} = (0.364)(106) + (0.636)(99) = 101.55$$

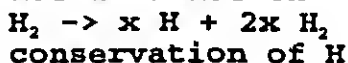
$$\text{MON} = (0.364)(92) + (0.636)(80) = 84.37$$

Eq. (4-9)

$$\text{AKI} = (\text{MON} + \text{RON}) / 2 = [(101.55) + (84.37)] / (2) = \underline{93.0}$$

(4-19)

(a) actual reaction



$$2 = x + 2x \quad x = \underline{0.40}$$

(b) Eq. (4-4) with $A = \text{H}_2$ and $C = \text{H}$

$$B = D = 0$$

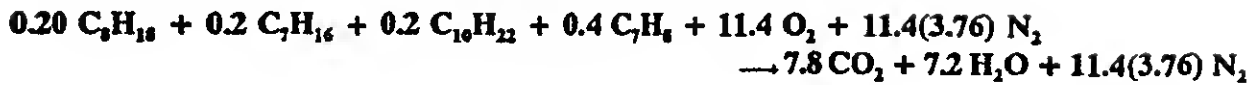
$$K_p = [(x^2)/(2x)][1/(x + 2x)]^{2-1} = 1/6 = \underline{0.1667}$$

(c) $\log_{10} K_p = -0.7781$

by interpolation in Table A-3 for reaction (A) $T = \underline{3362 \text{ K}}$

(4-20)

stoichiometric combustion equation using Table A-2



(a)

Eqs. (2-55) and (4-1)

$$AF = m_f/m_r = N_f M_f / N_r M_r$$

$$= [(11.4)(4.76)(29)] / [(0.2)(114) + (0.2)(100) + (0.2)(142) + (0.4)(92)] = \underline{14.57}$$

(b)

for 1 mole of fuel

	moles (N)	molecular weight(M)	mass m=NM	mass fraction
C_8H_{18}	0.2	114	22.8	0.211
C_7H_{16}	0.2	100	20.0	0.185
$\text{C}_{10}\text{H}_{22}$	0.2	142	28.4	0.263
C_7H_8	0.4	92	36.8	0.341
			<u>108.0</u>	<u>1.000</u>

108 = molecular weight of gas mixture

Eq. (4-11)

$$RON = (0.211)(100) + (0.185)(112) + (0.263)(113) + (0.341)(120) = \underline{112}$$

(c)

for 1 mole of fuel

$$Q_{LEV} = (22.8)(44,300) + (20.0)(44,440) + (28.4)(44,220) + (36.8)(40,600) \\ = 4,648,768 \text{ kJ/kgmole}$$

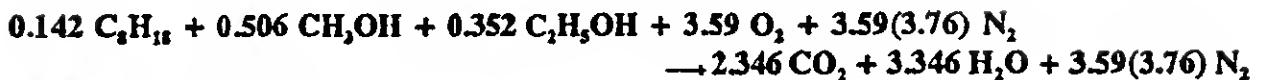
$$Q_{LEV} = (4,648,768 \text{ kJ/kgmole}) / (108 \text{ kg/kgmole}) = \underline{43,044 \text{ kJ/kg}}$$

(4-21)

using values from Table A-2

	mass (m)	molecular weight(M)	moles $N=m/M$	mole fraction
C_3H_{18}	1	114	0.00877	0.142
CH_3OH	1	32	0.03125	0.506
C_2H_5OH	1	46	<u>0.02174</u>	<u>0.352</u>
			0.06176	1.000

stoichiometric combustion equation for one mole of fuel



(a)

Eqs. (2-55) and (4-1)

$$AF = m_f/m_r = N_r M_r / N_f M_f \\ = [(3.59)(4.76)(29)] / [(0.142)(114) + (0.506)(32) + (0.352)(46)] = \underline{10.20}$$

(b)

Eqs. (4-11), (4-10) and (4-9)

$$MON = \frac{1}{3}(100) + \frac{1}{3}(92) + \frac{1}{3}(89) = \underline{93.7}$$

$$RON = \frac{1}{3}(100) + \frac{1}{3}(106) + \frac{1}{3}(107) = \underline{104.3}$$

$$FS = RON - MON = 104.3 - 93.7 = \underline{10.6}$$

$$AKI = (MON + RON)/2 = (93.7 + 104.3)/2 = \underline{99}$$

(4-22)

(a)

$$\text{Eq. (4-12)} \quad CN = (23) + (0.15)(77) = \underline{34.6}$$

(b)

$$\text{specific gravity} \quad s_g = \rho/\rho_{\text{water}} = 860/997 = 0.863$$

Eq. (4-13)

$$G = (141.5/0.863) - 131.5 = 32.46$$

$$T_{mp} = 229^\circ C = 444^\circ F$$

$$CI = -420.34 + 0.016 G^2 + 0.192 G(\log_{10} T_{mp}) + 65.01(\log_{10} T_{mp})^2 - 0.0001809 T_{mp}^2$$

$$= -420.34 + (0.016)(32.46)^2 + (0.192)(32.46)(\log_{10}[444]) + (65.01)(\log_{10}[444])^2 - (0.0001809)(444)^2 \\ = \underline{32.9}$$

$$\% \text{ error} = [(32.9 - 34.6)/34.6](100) = \underline{-4.91\%}$$

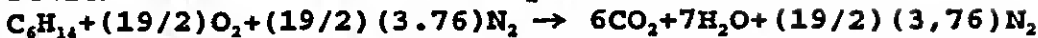
(4-23)

$$N = (2400/60 \text{ rev/sec})(360 \text{ deg/rev}) = 14,400 \text{ deg/sec}$$

$$ID = (15^\circ)/(14,400 \text{ deg/sec}) = \underline{0.0010 \text{ sec}}$$

(4-24)

(a) stoichiometric combustion equation



$$(AF)_{\text{stoich}} = [(19/2)(4.76)(29)]/[(1)(86)] = 15.25$$

Eq. (2-57)

$$\phi = (AF)_{\text{stoich}}/(AF)_{\text{act}} = (15.25)/(25) = \underline{0.610}$$

(b) Eq. (2-58)

$$\lambda = 1/\phi = (1)/(0.610) = \underline{1.64}$$

(c) Eq. (4-13)

$$T_{\text{mp}} = 69^\circ\text{C} = 156^\circ\text{F}$$

$$G = (141.5/S_g) - (131.5) = [(141.5)/(0.659)] - (131.5) = 83.2$$

$$\begin{aligned} CI &= -420.34 + 0.016G^2 + 0.192G(\log_{10}T_{\text{mp}}) + 65.01(\log_{10}T_{\text{mp}})^2 - 0.0001809T_{\text{mp}}^2 \\ &= (-420.34) + (0.016)(83.2)^2 + (0.192)(83.2)[\log_{10}(156)] \\ &\quad + (65.01)[\log_{10}(156)]^2 - (0.0001809)(156)^2 = \underline{33.7} \end{aligned}$$

(4-25)

(a) Eq. (4-14) gives ignition delay in crank angle degrees

$$E_A = (618,840)/(CN + 25) = (618,840)/(51 + 25) = 8143$$

$$ID = (.36 + .22U_p) \exp\{E_A[(1/R_u T_i r_c^{k-1}) - (1/17190)] [(21.2)/(P_i r_c^k - 12.4)]^{0.63}\}$$

$$= [0.36 + (0.22)(9.50)] \exp\{8143[(1/((8.314)(320)(16)^{1.35-1}) - (1/17,190))] [21.2/((1.1)(16)^{1.35} - 12.4)]^{0.63}\}$$

$$= 4.08^\circ$$

start of injection

$$x + (4.08^\circ) = 12^\circ \text{ bTDC}$$

$$\underline{x = 16.08^\circ \text{ bTDC}}$$

(b) Eq. (4-15)

$$ID(\text{ms}) = ID(\text{ca})/(0.006 N) = (4.08)/[(0.006)(1295)]$$

$$= \underline{0.525 \text{ ms}}$$

(4-26)

specific gravity

$$s_g = \rho/\rho_{\text{water}} = 720/997 = 0.722$$

Eq. (4-13)

$$G = (141.5/0.722) - 131.5 = 64.48$$

$$T_{\text{mp}} = 91^\circ \text{C} = 195.2^\circ \text{F}$$

$$CI = -420.34 + 0.016 G^2 + 0.192 G(\log_{10} T_{\text{mp}}) + 65.01(\log_{10} T_{\text{mp}})^2 - 0.0001809 T_{\text{mp}}^2$$

$$= -420.34 + (0.016)(64.48)^2 + (0.192)(64.48)(\log_{10}[195.2]) + (65.01)(\log_{10}[195.2])^2 - (0.0001809)(195.2)^2 = \underline{8.7}$$

(4-27)

$[\text{CO} + \frac{1}{2}(3.76)\text{N}_2]$ equals 2.88 moles of fuel

mass of fuel in 2.88 kgmoles using Eq. (4-1)

$$m_f = (1)(28) + (\frac{1}{2})(3.76)(28) = 80.64 \text{ kg}$$

mass of fuel in 1 kgmole = molecular weight

$$M = m/N = (80.64 \text{ kg})/(2.88 \text{ kgmoles}) = 28 \text{ kg/kgmole}$$

(a) higher heating value in 2.88 kgmoles of fuel

$$= [(28 \text{ kg})(10,100 \text{ kJ/kg})]_{\text{CO}} + [(\frac{1}{2})(3.76)(28 \text{ kg})(0 \text{ kJ/kg})]_{\text{N}_2} = 282,800 \text{ kJ}$$

higher heating value in 1 kgmole of fuel

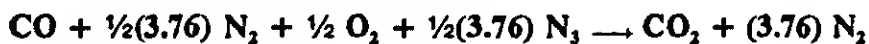
$$= (282,800 \text{ kJ})/(2.88 \text{ kgmoles}) = 98,194 \text{ kJ/kgmole}$$

higher heating value in mass units

$$Q_{\text{HHV}} = (98,194 \text{ kJ/kgmole})/(28 \text{ kg/kgmole}) = \underline{3507 \text{ kJ/kg}}$$

because there is no water vapor $Q_{\text{LHV}} = Q_{\text{HHV}} = \underline{3507 \text{ kJ/kg}}$

(b) stoichiometric combustion equation



Eqs. (2-55) and (4-1)

$$AF = m_a/m_f = N_a M_a / N_f M_f = [(\frac{1}{2})(4.76)(29)]/[(2.88)(28)] = \underline{0.856}$$

(c) no dew point as there is no water vapor

CHAPTER 5

(5-1)

(a) Eqs. (3-4) and (3-5)

$$T_2 = T_1(r_c)^{k-1} = (336 \text{ K})(11)^{0.35} = \underline{778 \text{ K} = 505^\circ \text{ C}}$$

$$P_2 = P_1(r_c)^k = (92 \text{ kPa})(11)^{1.35} = \underline{2342 \text{ kPa}}$$

(b) crankshaft offset = $a = S/2 = 5.72/2 = 2.86 \text{ cm}$

$$R = r/a = 11.0/2.86 = 3.85$$

crank angle when intake valve closes and actual compression starts

$$\theta = 180^\circ + 41^\circ = 221^\circ$$

crank angle when ignition occurs $\theta = 345^\circ$

using Eq. (2-14) for combustion chamber volume when intake valve closes

$$V_{\text{IVO}}/V_c = 1 + \frac{1}{2}(r_c - 1)[R + 1 - \cos\theta - (R^2 - \sin^2\theta)^{1/2}]$$

$$V_{\text{IVO}}/V_c = 1 + \frac{1}{2}(11 - 1)\{(3.85) + (1) - \cos(221^\circ) - [(3.85)^2 - \sin^2(221^\circ)]^{1/2}\} = 10.05$$

combustion chamber volume when ignition occurs

$$V_{\text{IG}}/V_c = 1 + \frac{1}{2}(11 - 1)\{(3.85) + (1) - \cos(345^\circ) - [(3.85)^2 - \sin^2(345^\circ)]^{1/2}\} = 1.214$$

effective compression ratio

$$V_{\text{IVO}}/V_{\text{IG}} = (V_{\text{IVO}}/V_c)/(V_{\text{IG}}/V_c) = (10.05)/(1.214) = 8.28$$

$$(c) \quad T_2 = (336 \text{ K})(8.28)^{1.35-1} = \underline{704 \text{ K} = 431^\circ \text{ C}}$$

$$P_2 = (92 \text{ kPa})(8.28)^{1.35} = \underline{1596 \text{ kPa}}$$

(5-2)

(a) using Fig. 3-5 and Eq. (3-4)

$$T_2 = T_1(r_c)^{k-1} = (333 \text{ K})(10.5)^{0.35} = 758 \text{ K} = \underline{485^\circ \text{ C}}$$

$$(b) \quad \text{Eq. (3-4)} \quad 758 \text{ K} = (353 \text{ K})(r_c)^{0.35} \quad r_c = \underline{8.88}$$

(c) using Fig. 5-19 and Eq. (5-15) with $k = 1.4$

$$T_{2s} = T_1(P_2/P_1)^{(k-1)/k} = (333 \text{ K})(130/96)^{(1.4-1)/1.4} = 363 \text{ K}$$

$$\text{Eq. (5-14)} \quad (\eta_s)_c = (T_{2s} - T_1)/(T_{2A} - T_1)$$

$$0.82 = (363 - 333)/(T_{2A} - 333) \quad T_{2A} = 370 \text{ K} = 97^\circ \text{ C}$$

$$\Delta T = T_{2A} - T_{\text{inlet}} = 97^\circ - 80^\circ = \underline{17^\circ \text{ C}}$$

(5-3)

(a)

use Eq. (2-57) for actual air-fuel ratio

$$(AF)_{act} = (AF)/\phi = 14.6/0.95 = 15.37$$

using low temperature value of c_p

$$Q_{evap} = m_f h_g = m_m c_p \Delta T = (m_a + m_f) c_p \Delta T$$

$$h_g = [(m_a + m_f)/m_f] c_p \Delta T = (AF + 1) c_p \Delta T$$

$$(307 \text{ kJ/kg}) [0.4299 \text{ (BTU/lbm)} / (\text{kJ/kg})] = (16.37)(0.240 \text{ BTU/lbm} \cdot ^\circ\text{R}) \Delta T$$

$$\Delta T = 34^\circ \text{ F}$$

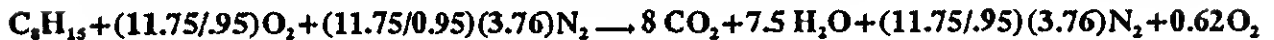
$$T_2 = T_1 - \Delta T = 74^\circ - 34^\circ = \underline{40^\circ \text{ F}} = 500^\circ \text{ R}$$

(b)

stoichiometric combustion reaction



combustion reaction with equivalence ratio $\phi = 0.95$



this reduces to



volume flow of air is reduced by volume of fuel vapor

in molar quantities volume flow of air with evaporation

$$\begin{aligned} (\dot{V}ol_a)_{with} &= (\dot{V}ol_a)_1 (N_{without}/N_{with}) = [(12.37)(4.76)] / [(12.37)(4.76) + 1] \\ &= 0.983 (\dot{V}ol_a)_1 \end{aligned}$$

this volume flow rate is now increased by reduction in temperature

$$(\dot{V}ol_a)_{final} = [0.983 (\dot{V}ol_a)_1] [(534^\circ \text{ R}) / (500^\circ \text{ R})] = 1.050 (\dot{V}ol_a)_1$$

5.0% increase in η .

(c)

Eq. (3-50)

$$T_2 = x_r T_{ex} + (1 - x_r) T_a = (0.05)(900^\circ \text{ R}) + (1 - 0.05)(500^\circ \text{ R}) = 520^\circ \text{ R} = \underline{60^\circ \text{ F}}$$

(5-4)

(a) cooling with water evaporation

$$Q_{evap} = m_w h_g = m_w c_p \Delta T = (m_a + m_f + m_w) c_p \Delta T$$

$$h_g = \{[m_a + m_f + m_w]/m_w\} c_p \Delta T = \{[m_a + m_f + (m_f/30)]/(m_f/30)\} c_p \Delta T = [30(AF) + 31] c_p \Delta T$$

$$1052 \text{ BTU/lbm} = [30(15.37) + 31](0.240 \text{ BTU/lbm} \cdot ^\circ\text{R}) \Delta T$$

$$\Delta T = 9^\circ \text{F}$$

$$T = T_2 - \Delta T = 40^\circ - 9^\circ = 31^\circ\text{F} = 491^\circ\text{R}$$

(b) volume flow of air is reduced by volume of water vapor

moles of water for 1 mole of fuel using Eq. (4-1)

$$m_f/m_w = 30 = N_f M_f / N_w M_w = (1)(111) / N_w (18) \quad N_w = 0.206$$

for every mole of fuel there are 0.206 moles of water vapor

original volume flow of air is reduced by both fuel vapor and water vapor

In molar quantities volume flow of air with evaporation

$$\begin{aligned} (\text{Vol}_a)_{\text{with}} &= (\text{Vol}_a)_1 (N_{\text{without}} / N_{\text{with}}) \\ &= (\text{Vol}_a)_1 [(12.37)(4.76)] / [(12.37)(4.76) + 1.206] = 0.980 (\text{Vol}_a)_1 \end{aligned}$$

this volume flow rate is now increased by reduction in temperature

$$(\text{Vol}_a)_{\text{final}} = (\text{Vol}_a)_1 [(534^\circ \text{R}) / (495^\circ \text{R})] = 1.057 (\text{Vol}_a)_1$$

5.7% Increase in η .

(5-5)

- (a) When a turbocharger is used cylinder inlet air temperature is usually higher due to compressive heating, depending on amount of aftercooling. The compression ratio is often then reduced to lower the additional compressive heating that occurs during the compression stroke. If this were not done there would be a chance of combustion temperature becoming too high with resulting self-ignition and knock problems.
- (b) Brake power could be increased or decreased depending on amount of pressure increase, aftercooling, compression ratio change, and exhaust pressure increase due to turbine of turbocharger.
- (c) By air-standard Otto cycle analysis reducing the compression ratio will lower the indicated thermal efficiency [Eq. (3-31)]. However, greater indicated power generated in the cylinders along with basically the same mechanical efficiency will increase real brake thermal efficiency.
- (d) Engine knock is not a problem in CI engines.

(5-6)

for 1 cylinder

$$V_d = (2.4 \text{ L})/4 = 0.6 \text{ L} = 0.0006 \text{ m}^3$$

(a)

using Eq. (2-71) for air flow rate into one cylinder at WOT
 $\dot{m}_a = \rho_a V_d N \eta_v / n = (1.181)(0.0006)(5800/60)(0.95)/2 = 0.03254 \text{ kg/sec}$

Eq. (2-55) gives fuel flow rate into 1 cylinder which is the flow rate through an injector
 $\dot{m}_f = \dot{m}_a / AF = (0.03254 \text{ kg/sec})/14.6 = \underline{0.00223 \text{ kg/sec}}$

(b)

using Eq. (2-71) for air flow rate into one cylinder at WOT

Eq. (2-71) for air flow rate into one cylinder at idle

$$\dot{m}_a = [(1.181)(30/101)(0.0006)(600/60)]/(2) = 0.001052 \text{ kg/sec}$$

Eq. (2-55) gives fuel flow into one cylinder

$$\dot{m}_f = (0.001052 \text{ kg/sec})/(14.6) = 0.0000721 \text{ kg/sec}$$

fuel flow into one cylinder for one cycle at idle

$$\dot{m}_f = (0.0000721 \text{ kg/sec})(2 \text{ rev/cycle})/(600/60 \text{ rev/sec}) = 0.0000144 \text{ kg/cycle}$$

time of injection

$$t = (0.0000144 \text{ kg})/(0.00223 \text{ kg/sec}) = \underline{0.0065 \text{ sec}}$$

(c)

rotational speed at idle

$$(600/60 \text{ rev/sec})(360^\circ/\text{rev}) = 3600^\circ/\text{sec}$$

$$\text{time of injection} = (3600^\circ/\text{sec})(0.0065 \text{ sec}) = \underline{23.4^\circ}$$

(5-7)

use Eq. (2-57) to get actual AF ratio

$$(AF)_{act} = (AF)_{stoich}/\phi = 9.0/1.06 = 8.49$$

$$\text{for 1 cylinder} \quad V_d = (2.4 \text{ L})/6 = 0.4 \text{ L} = 0.0004 \text{ m}^3$$

(a)

Eq. (2-70) gives mass of air into one cylinder for one cycle
 $m_a = \rho_a V_d \eta_v = (1.181 \text{ kg/m}^3)(0.0004 \text{ m}^3)(0.87) = 0.000411 \text{ kg}$

Eq. (2-55) gives mass of fuel into 1 cylinder for 1 cycle
 $m_f = m_a/(AF)_a = (0.000411 \text{ kg})/8.49 = 0.0000484 \text{ kg}$

$$\text{time of injection} = (0.0000484 \text{ kg})/(0.02 \text{ kg/sec}) = \underline{0.00242 \text{ sec}}$$

(b)

$$\text{actual AF from above} \quad \underline{(AF)_a = 8.49}$$

(c)

when auxillary injector is used at 3000 RPM

time of 1 cycle

$$t = (2 \text{ rev/cycle})/(3000/60 \text{ rev/sec}) = 0.04 \text{ sec/cycle}$$

mass of fuel from port injector for 1 cylinder for 1 cycle

$$m_f = 0.0000484 \text{ kg}$$

mass of fuel from auxilliary injector for 1 cyl for 1 cycle

$$m_f = (0.003 \text{ kg/sec})(0.04 \text{ sec})/(6 \text{ cylinders}) = 0.000020 \text{ kg}$$

Eq. (2-55) for 1 cylinder for 1 cycle

$$AF = m_a/m_f = 0.000411/(0.0000484 + 0.000020) = \underline{6.01}$$

(5-8)

Temperature of the air-fuel mixture at intake manifold exit could either increase or decrease as engine speed is increased. The mixture will pass through the manifold quicker allowing less time for heating from the hotter walls. However, a higher flow rate will increase the convection heat transfer rate. Also at higher speed engine components, including intake manifold, will be hotter. The amount of fuel that vaporizes in the manifold will change, changing the amount of evaporative cooling. Exit temperature will depend on many parameters including engine speed increase, engine geometry, type of fuel, air-fuel ratio, etc.

(5-9)

use Eq. (2-70) to get air flow rate needed at max speed

$$\dot{m}_a = \rho_a V_a N \eta_v / n = (1.181)(0.0062)(6500/60)(0.88)/2 = 0.349 \text{ kg/sec}$$

for each of 4 barrels

$$\dot{m}_a = (0.349 \text{ kg/sec})/4 = 0.0873 \text{ kg/sec}$$

(a)

use Eq. (5-12) for throat area of 1 barrel

$$(\dot{m}_a)_{\max} = 236.5 C_{D_t} [A_t] = 0.0873 = (236.5)(0.95) [A_t]$$

$$A_t = 0.0003886 \text{ m}^2 = 3.886 \text{ cm}^2 = (\pi/4)d_t^2$$

$$\underline{d_t = 2.224 \text{ cm}}$$

(b)

Eq. (2-55) gives fuel flow rate needed for 1 barrel

$$\dot{m}_f = \dot{m}_a / (AF) = (0.0873 \text{ kg/sec})/15 = 0.00582 \text{ kg/sec}$$

Eq. (5-10) gives pressure in carburetor throat

$$P_t = (0.5283)P_o = (0.5283)(101 \text{ kPa}) = 53.4 \text{ kPa}$$

Eqs. (5-6) and (5-7) give pressure differential in fuel capillary

$$\Delta P_f = \Delta P_s = P_o - P_t = 101 - 53.4 = 47.6 \text{ kPa}$$

use Eq. (5-8) for fuel capillary tube flow area

$$\dot{m}_f = C_{D_c} A_c [2\rho_f \Delta P_f]^{1/2}$$

$$0.00582 \text{ kg/sec} = (0.85)A_c [(2)(750 \text{ kg/m}^3)(47.6 \text{ kN/m}^2)(1 \text{ kg}\cdot\text{m/N}\cdot\text{sec}^2)]^{1/2}$$

$$A_c = 0.00000081 \text{ m}^2 = 0.81 \text{ mm}^2 = (\pi/4)d_c^2$$

$$\underline{d_c = 1.016 \text{ mm}}$$

(5-10)

- (a) The choke is first closed by stepping the accelerator pedal fully down. The closed choke creates a high vacuum downstream through the carburetor. This causes a high fuel flow rate through both the fuel capillary tube and the idle valve. With a low air flow rate the resulting air-fuel mixture is very fuel-rich. Because only a very small percent of the fuel evaporates in the cold engine intake, the rich mixture is needed to assure a combustible air-fuel vapor mixture.**
- (b) When an automobile is accelerated the throttle valve is quickly opened to increase air intake rate. The gaseous air inflow rate increases quickly but the increase rate of the liquid fuel droplets and wall film is slower due to the higher mass inertia of the liquid. This would result in a fuel-lean mixture and poor acceleration. An accelerator pump adds additional fuel at this time to avoid the fuel deficiency that would occur. The result is a fuel-rich mixture which is desirable during acceleration.**
- (c) When the carburetor throttle is closed to decelerate an automobile which is traveling at high speed a large vacuum is created in the intake system. The engine is turning at high speed but there is very little air flow into the engine. Exhaust gases back flow into the intake manifold due to the low pressure there. This results in a high exhaust residual remaining in the cylinders for the next cycle. The low pressure after the throttle valve in the carburetor causes a fuel flow through the idle valve. This fuel mixes with the low air flow giving a fuel-rich mixture into the engine. This rich mixture is needed to give acceptable combustion because of the large exhaust residual.**

(5-11)

(a)

Eq. (5-3) with 1 intake valve

$$(A_v)_1 = \pi d_v l = \pi (3.4 \text{ cm}) [(0.22)(3.4 \text{ cm})] = 7.99 \text{ cm}^2$$

with two Intake valves

$$(A_v)_2 = (2 \text{ valves}) \pi (2.7 \text{ cm}) [(0.22)(2.7 \text{ cm})] = 10.08 \text{ cm}^2$$

increase in flow area

$$\Delta A = (10.08 \text{ cm}^2) - (7.99 \text{ cm}^2) = \underline{2.09 \text{ cm}^2}$$

(b)

Advantages:

Greater Intake valve flow area which Improves volumetric efficiency.

Greater exhaust valve flow area which allows for a shorter exhaust blowdown process.

Greater flexibility in intake be allowing variation in valve timing and lift between the two valves.

Disadvantages:

Need for greater number and/or more complex camshafts.

Higher cost in manufacturing.

Difficulty of fitting valves into combustion chamber surface.

(5-12)

(a)

Eq. (5-27) gives mass flow rate through injector

$$\begin{aligned} \dot{m}_f &= C_D A_n [2 \rho_f \Delta P]^{1/2} \\ &= (0.72) [(\pi/4) (0.073 \text{ mm})^2] [2 (860 \text{ kg/m}^3) (50 - 5 \text{ MPa}) (1 \text{ kg-m/N-sec}^2)]^{1/2} = 0.000838 \text{ kg/sec} \end{aligned}$$

$$\begin{aligned} \dot{m}_f &= 0.000838 \text{ kg/sec} = \rho_f (\text{Vel}) A = (860 \text{ kg/m}^3) (\text{Vel}) [(\pi/4) (0.073 \text{ mm})^2] \\ \text{Vel} &= \underline{233 \text{ m/sec}} \end{aligned}$$

(b)

$$\text{distance to travel } x = B/2 = (8.2 \text{ cm})/2 = 4.1 \text{ cm} = 0.041 \text{ m}$$

$$\text{time} = (0.041 \text{ m}) / (233 \text{ m/sec}) = \underline{0.00018 \text{ sec}}$$

(5-13) for 1 cylinder using Eq. (2-8)

$$V_d = 3.6/6 = 0.6 \text{ L} = 0.0006 \text{ m}^3 = (\pi/4)B^2S = (\pi/4)(1.06)B^3$$

$$B = 0.0897 \text{ m} = 8.97 \text{ cm} \quad S = (1.06)(8.97 \text{ cm}) = 9.50 \text{ cm}$$

(a) sonic velocity at inlet conditions using Eq. (3-1j)

$$c = [kRT]^{1/2} = [(1.40)(287 \text{ J/kg}\cdot\text{K})(333 \text{ K})]^{1/2} = 366 \text{ m/sec}$$

Eq. (2-2) gives average piston velocity at maximum speed

$$(\bar{U}_p)_{\max} = 2SN = (2 \text{ strokes/cycle})(0.0950 \text{ m/stroke})(7000/60 \text{ rev/sec}) = 22.17 \text{ m/sec}$$

Eq. (5-4) gives area for the 2 valves

$$A_1 = CB^2[(\bar{U}_p)_{\max}/c] = (1.3)(8.97 \text{ cm})^2(22.17 \text{ m/sec})/(366 \text{ m/sec}) = 6.34 \text{ cm}^2$$

using Eqs. (5-1) and (5-3) for 1 valve

$$A_1 = 6.34/2 = 3.17 \text{ cm}^2 = \pi d_v l = \pi d_v (d_v/4) = (\pi/4)d_v^2 \quad \underline{d_v = 2.01 \text{ cm}}$$

(b) maximum flow velocity will be sonic $\underline{V_{\max} = c = 366 \text{ m/sec}}$ from above

(c) with proper design valves could be fit into combustion chamber with difficulty

(5-14)

mass of fuel in 1 Injection from Example Problem 5-4 $m_f = 0.0000396 \text{ kg}$

mass of 1 fuel droplet $m_f = (\text{Vol})\rho_f = (3 \times 10^{-14} \text{ m}^3)(860 \text{ kg/m}^3) = 2.580 \times 10^{-11} \text{ kg}$

(a) # of droplets = $(0.0000396 \text{ kg})/(2.580 \times 10^{-11} \text{ kg/droplet}) = \underline{1.535 \times 10^6 \text{ droplets}}$

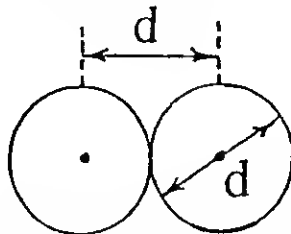
(b) from Example Problem 5-9 $V_d = 0.00064 \text{ m}^3$ for one cylinder
use Eq. (2-12) to find clearance volume

$$r_c = 18 = (V_c + V_d)/V_c = (V_c + 0.00064)/V_c \quad V_c = 0.0000376 \text{ m}^3$$

volume occupied by 1 droplet = $\text{Vol} = V_f/\# = 0.0000376 \text{ m}^3/1.535 \times 10^6 = 2.450 \times 10^{-11} \text{ m}^3$

if volume occupied by droplet is assumed a sphere

$$\text{Vol} = (\pi/6)d^3 = 2.450 \times 10^{-11} \text{ m}^3 \quad d = 0.000360 \text{ m} = 0.360 \text{ mm}$$



distance between droplets will be about equal to sphere diameter

$$\underline{\text{distance} \approx 0.360 \text{ mm}}$$

(5-15)

(a)

$$\begin{aligned} & \text{Eq. (2-71)} \\ & \dot{m}_a = \eta_v \rho_a V_d N / n \\ & = (0.61) (1.181 \text{ kg/m}^3) (0.0022 \text{ m}^3/\text{cycle}) (2100/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ & \quad = \underline{0.0277 \text{ kg/sec}} \end{aligned}$$

(b)

$$\begin{aligned} & \text{Eq. (2-55) for fuel flow rate into engine} \\ & \dot{m}_f = \dot{m}_a / \text{AF} = (0.0277 \text{ kg/sec}) / (21) = 0.00132 \text{ kg/sec} \end{aligned}$$

$$\begin{aligned} & \text{Eq. (2-65) gives brake power with this fuel flow rate} \\ & \dot{W}_b = \eta_c \dot{m}_f Q_{HV} \eta_c = (0.45) (0.00132 \text{ kg/sec}) (42,500 \text{ kJ/kg}) (0.98) = 24.75 \text{ kW} \end{aligned}$$

$$\begin{aligned} & \text{same equation to find fuel flow rate for two-cylinder engine} \\ & (24.75 \text{ kW}) = (0.42) \dot{m}_f (42,500 \text{ kJ/kg}) (0.98) \quad \dot{m}_f = 0.001415 \text{ kg/sec} \end{aligned}$$

$$\begin{aligned} & \text{Eq. (2-55) gives air flow rate needed} \\ & \dot{m}_a = \dot{m}_f (\text{AF}) = (0.001415 \text{ kg/sec}) (21) = \underline{0.0297 \text{ kg/sec}} \end{aligned}$$

(c)

$$\begin{aligned} & \text{Eq. (2-71) gives engine speed for this air flow rate} \\ & (0.0297 \text{ kg/sec}) = (0.82) (1.181 \text{ kg/m}^3) (0.0011 \text{ m}^3/\text{cycle}) (N/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ & \quad \underline{N = 3348 \text{ RPM}} \end{aligned}$$

(5-16)

(a)

$$\begin{aligned} & \text{engine speed at 3000 RPM} \\ & (3000/60 \text{ rev/sec}) (360^\circ/\text{rev}) = 18,000^\circ/\text{sec} \end{aligned}$$

$$\begin{aligned} & \text{crank angle rotation in 0.004 seconds} \\ & \angle = (18,000^\circ/\text{sec}) (0.004 \text{ sec}) = 72^\circ \end{aligned}$$

$$\begin{aligned} & \text{angle when intake valve opens} \\ & x + 72^\circ = 20^\circ \text{ aTDC} \quad \underline{x = 52^\circ \text{ bTDC}} \end{aligned}$$

(b)

$$\begin{aligned} & \text{engine speed at 1200 RPM} \\ & (1200/60 \text{ rev/sec}) (360^\circ/\text{rev}) = 7200^\circ/\text{sec} \end{aligned}$$

$$\begin{aligned} & \text{crank angle rotation in 0.002 seconds} \\ & \angle = (7200^\circ/\text{sec}) (0.002 \text{ sec}) = 14.4^\circ \end{aligned}$$

$$\begin{aligned} & \text{angle when intake valve opens} \\ & x + 14.4^\circ = 20^\circ \text{ aTDC} \quad \underline{x = 5.6^\circ \text{ aTDC}} \end{aligned}$$

(5-17)

(a)

Eq. (2-71)

$$\begin{aligned}\dot{m}_a &= \eta_v \rho_a V_d N / n \\ &= (0.93) (1.181 \text{ kg/m}^3) (0.460 \text{ m}^3 / \text{cycle}) (195/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ &= \underline{1.642 \text{ kg/sec}}\end{aligned}$$

(b)

Eq. (2-55)

$$\dot{m}_f = \dot{m}_a / \text{AF} = [(1.642 \text{ kg/sec}) (0.92)] / (6.5) = \underline{0.232 \text{ kg/sec}}$$

(c)

average flow rate of diesel fuel

$$\dot{m}_{df} = [(1.642 \text{ kg/sec}) (0.08)] / (14.5) = 0.00906 \text{ kg/sec}$$

diesel fuel for one cylinder for one cycle

$$\begin{aligned}m &= (0.00906 \text{ kg/sec}) / [(195/60 \text{ rev/sec}) (12 \text{ cylinders}) (1 \text{ cycle/rev})] \\ &= 0.000232 \text{ kg/cycle-cyl}\end{aligned}$$

$$\text{engine speed} = (195/60 \text{ rev/sec}) (360^\circ/\text{rev}) = 1170^\circ/\text{sec}$$

$$\text{time of one injection} \quad t = (21^\circ) / (1170^\circ/\text{sec}) = 0.0180 \text{ sec}$$

flow rate through injector

$$\dot{m}_f = (0.000232 \text{ kg}) / (0.0180 \text{ sec}) = \underline{0.0130 \text{ kg/sec}}$$

(5-18)

(a)

air-fuel mass trapped in cylinder after valves are closed

$$m_{at} = (0.000440 \text{ kg}) (1 - 0.046) = 0.000420 \text{ kg}$$

Eq. (5-24) gives mass of air-fuel ingested

$$m_{ai} = m_{at} / \lambda_{te} = (0.000420 \text{ kg}) / (0.760) = 0.000553 \text{ kg}$$

Eq. (5-22)

$$\lambda_{dr} = m_{ai} / V_d \rho_a = (0.000553 \text{ kg}) / [(0.0015/3 \text{ m}^3) (1.181 \text{ kg/m}^3)] = \underline{0.936}$$

(b)

Eq. (5-23)

$$\lambda_{ce} = m_{at} / V_d \rho_a = (0.000420 \text{ kg}) / [(0.0005 \text{ m}^3) (1.181 \text{ kg/m}^3)] = \underline{0.711}$$

(c)

Eq. (5-25)

$$\lambda_{ss} = m_{at} / m_{tc} = (0.000420 \text{ kg}) / (0.000440 \text{ kg}) = \underline{0.955}$$

(d)

Eq. (5-26)

$$\begin{aligned}\lambda_{rc} &= m_{tc} / V_d \rho_a = \lambda_{ce} / \lambda_{ss} \\ &= (0.000440 \text{ kg}) / [(1.181 \text{ kg/m}^3) (0.0005 \text{ m}^3)] = (0.711) / (0.955) \\ &= \underline{0.745}\end{aligned}$$

(5-19)

(a)

Eq. (5-22) gives air-fuel flow into engine

$$\dot{m}_{a,i} = \lambda_{dr} V_d \rho_a = (0.95)(0.003 \text{ m}^3)(1.181 \text{ kg/m}^3) = 0.1683 \text{ kg/sec}$$

air flow only

$$\dot{m}_a = (0.1683 \text{ kg/sec})[(14.6)/(15.6)] = \underline{0.1575 \text{ kg/sec}}$$

(b)

fuel flow into engine

$$\dot{m}_f = (0.1683 \text{ kg/sec})[(1)/(15.6)] = 0.0108 \text{ kg/sec}$$

oil flow into engine

$$\dot{m}_o = (0.0108 \text{ kg/sec})/(25) = \underline{0.00043 \text{ kg/sec}}$$

(c)

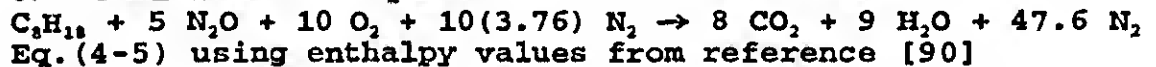
85% of intake is trapped and burned,

15% escapes during scavenging

$$\dot{m}_b = (0.00043 \text{ kg/sec})(0.15) = \underline{0.000065 \text{ kg/sec} = 0.23 \text{ kg/hr}}$$

(5-20)

chemical reaction equation with nitrous oxide



$$\begin{aligned} Q_{in} &= \sum_{\text{PROD}} N_i H_i - \sum_{\text{REACT}} N_i H_i \\ &= (8)[(-393,522) + (33,397)] + (9)[(-241,826) + (26,000)] \\ &\quad + (47.6)[(0) + (21,463)] - (1)[(-259,280) + (0)] \\ &\quad - (5)[(-81,600) + (0)] - (10)[(0) + (0)] - (37.6)[(0) + (0)] \\ &= -3,134,515 \text{ kJ} \end{aligned}$$

this heat amount is increased because of less air required

$$Q_{in} = (-3,134,515 \text{ kJ})[(12.5)/(10)] = -3,918,144 \text{ kJ}$$

cooling by evaporation of nitrous oxide

$$mc_p \Delta T = h_{fg}(\text{number of moles})$$

$$10(4.76) \text{ kgmoles} (29 \text{ kg/kgmole}) (1.005 \text{ kJ/kg-K}) \Delta T = (11,037 \text{ kJ/kgmole}) (5 \text{ kgmoles})$$

$$\Delta T = 40 \text{ K} \quad T_{\text{final}} = 298 \text{ K} - 40 = 258 \text{ K}$$

this increases density of air and increases heat in

$$Q_{in} = (-3,918,144 \text{ kJ})[(298)/(258)] = -4,525,608 \text{ kJ}$$

$$\Delta\% = [(4,525,600 - 3,555,000)/(3,555,000)](100) = \underline{27.3\% \text{ increase}}$$

200 kW becomes 255 kW

CHAPTER 6

(6-1)

Eq. (2-8) for 1 cylinder

$$V_d = 2.4/3 = 0.8 \text{ L} = 0.0008 \text{ m}^3 = (\pi/4)B^2S = (\pi/4)B^2(0.0979 \text{ m})$$

$$B = 0.102 \text{ m} = 10.2 \text{ cm}$$

Eq. (6-1) during compression stroke

$$(SR)_1 = \omega/N = 4.8 = \omega/(2100/60 \text{ rev/sec})$$

$$\omega = 168 \text{ rev/sec}$$

Eq. (6-3) gives mass moment of inertia during compression

$$I = mB^2/8 = (0.001 \text{ kg})((0.102 \text{ m})^2/8 = 1.30 \times 10^{-6} \text{ kg}\cdot\text{m}^2$$

Eq. (6-4) gives angular momentum

$$\Gamma = I\omega = (1.30 \times 10^{-6} \text{ kg}\cdot\text{m}^2)(168 \text{ rev/sec})(2\pi \text{ radians/rev}) = 0.001372 \text{ kg}\cdot\text{m}^2/\text{sec}$$

(a)

mass moment of inertia at TDC

$$I = (0.001 \text{ kg})(0.060 \text{ m})^2/8 = 4.50 \times 10^{-7} \text{ kg}\cdot\text{m}^2$$

using Eq. (6-4) keeping angular momentum constant

$$\omega = \Gamma/I = (0.001372 \text{ kg}\cdot\text{m}^2/\text{sec})/[(4.5 \times 10^{-7} \text{ kg}\cdot\text{m}^2)(2\pi \text{ radians/rev})] = \underline{485 \text{ rev/sec}}$$

(b)

$$u_t = \omega r = (485 \text{ rev/sec})(2\pi \text{ radians/rev})(0.03 \text{ m}) = \underline{91.4 \text{ m/sec}}$$

(c)

Eq. (2-2)

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.0979 \text{ m/stroke})(2100/60 \text{ rev/sec}) = 6.853 \text{ m/sec}$$

Eq. (6-2)

$$(SR)_2 = u_t/\bar{U}_p = (91.4 \text{ m/sec})/(6.853 \text{ m/sec}) = \underline{13.3}$$

(6-2) Eq. (2-8) for 1 cylinder

$$V_d = 150/4 = 37.5 \text{ in.}^3 = (\pi/4)B^2S = (\pi/4)B^2(0.95 B)$$

$$B = 3.69 \text{ in.} \quad S = (0.95)(3.69 \text{ in.}) = 3.51 \text{ in.}$$

Eq. (2-2) gives average piston speed

$$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(3.51 \text{ in./stroke})(3600/60 \text{ rev/sec}) = 421.2 \text{ in./sec} = 35.1 \text{ ft/sec}$$

(a) Eq. (6-2)

$$(SR)_1 = 8 = u_t/\bar{U}_p = u_t/(35.1 \text{ ft/sec}) \quad \underline{u_t = 281 \text{ ft/sec}}$$

(b) $u_t = \omega r = 281 \text{ ft/sec} = \omega(2\pi \text{ radians/rev})(3.69/2 \text{ in.})/(12 \text{ in./ft})$
 $\underline{\omega = 291 \text{ rev/sec}}$

(c) $(SR)_1 = \omega/N = (291 \text{ rev/sec})/(3600/60 \text{ rev/sec}) = \underline{4.85}$

(6-3)

(a)

Eq. (6-1)

$$(SR)_1 = \omega/N = (250 \text{ rev/sec})/(2800/60 \text{ rev/sec}) = \underline{5.36}$$

(b)

$$S = 0.92 B = (0.92)(0.0856 \text{ m}) = 0.07875 \text{ m}$$

Eq. (2-2)

$$\bar{U}_p = 2SN$$

$$= (2 \text{ strokes/rev})(0.07875 \text{ m/stroke})(2800/60 \text{ rev/sec}) = 7.35 \text{ m/sec}$$

tangential speed

$$u_t = \omega r = (250 \text{ rev/sec})(2\pi \text{ radians/rev})(0.0428 \text{ m}) = 67.23 \text{ m/sec}$$

Eq. (6-2)

$$(SR)_2 = u_t/\bar{U}_p = (67.23 \text{ m/sec})/(7.35 \text{ m/sec}) = \underline{9.15}$$

(c)

Eq. (6-3) during compression

$$I_1 = mB^2/8 = (\text{mass})(0.856 \text{ m})^2/(8) = (\text{mass})(0.000916 \text{ m}^2)$$

at TDC

$$I_2 = (\text{mass})(0.050 \text{ m})^2/(8) = (\text{mass})(0.0003125 \text{ m}^2)$$

conservation of momentum using Eq. (6-4)

$$\Gamma_1 = \Gamma_2$$

$$I_1\omega_1 = I_2\omega_2$$

$$(\text{mass})(0.000916 \text{ m}^2)(250 \text{ rev/sec}) = (\text{mass})(0.0003125 \text{ m}^2)\omega_2$$

$$\underline{\omega_2 = 732.8 \text{ rev/sec}}$$

(6-4)

(a)

Eq. (6-5)

$$\omega_t = (TR)N = (1.78)(3200/60 \text{ rev/sec}) = 94.93 \text{ rev/sec}$$

tangential velocity

$$u_t = \omega_t r = (94.93 \text{ rev/sec})(2\pi \text{ radians/rev})(0.0090 \text{ m}) = \underline{5.37 \text{ m/sec}}$$

(b)

Eq. (6-3)

$$I = mB^2/8 = (0.0012 \text{ kg})(0.0180 \text{ m})^2/8 = 4.86 \times 10^{-8} \text{ kg-m}^2$$

rotational kinetic energy

$$KE = I\omega^2/2g_c$$

$$= 4.86 \times 10^{-8} \text{ kg-m}^2 [(94.93 \text{ rev/sec})(2\pi \text{ radians/rev})]^2 / [2(1 \text{ kg-m/N-sec}^2)] \\ = \underline{0.00865 \text{ N-m} = 0.00865 \text{ J}}$$

(6-5)

(a)

at end of compression

$$T_2 = T_1(r_c)^{k-1} = (333 \text{ K})(10.2)^{1.35-1} = 751 \text{ K}$$

$$P_2 = P_1(r_c)^k = (100 \text{ kPa})(10.2)^{1.35} = 2299 \text{ kPa}$$

mass in crevice

$$m_{\text{crev}} = P_{\text{Vcrev}}/RT$$

$$= (2299 \text{ kPa})[(0.03)V_2] / [(0.287 \text{ kJ/kg-K})(453 \text{ K})] = 0.5305 V_2$$

mass in clearance volume

$$m_{\text{clear}} = PV/RT = (2299 \text{ kPa})V_2 / [(0.287 \text{ kJ/kg-K})(751 \text{ K})] = 10.666 V_2$$

percent mass in crevice

$$\% = \{(0.5305 V_2) / [(0.5305 V_2) + (10.666 V_2)]\}(100) = \underline{4.74\%}$$

(b)

$$m = (0.0042 \text{ kg/sec})(0.0474 \text{ trapped})(0.15 \text{ not burned})(3600 \text{ sec/hr}) \\ = \underline{0.1075 \text{ kg/hr}}$$

(c)

$$\text{Energy} = mQ_{\text{HV}} = [(0.0042)(0.0474)(0.15) \text{ kg/sec}](43,000 \text{ kJ/kg}) \\ = \underline{1.28 \text{ kJ/sec} = 1.28 \text{ kW}}$$

(6-6)

Eqs. (3-4) and (3-5) and Fig. 3-2

$$T_2 = T_1(r_c)^{k-1} = (338 \text{ K})(10.9)^{0.35} = 780 \text{ K}$$

$$P_2 = P_1(r_c)^k = (98 \text{ kPa})(10.9)^{1.35} = 2465 \text{ kPa}$$

(a) mass in combustion chamber (clearance volume) at TDC

$$m_{cc} = PV_c/RT = (2465 \text{ kPa})V_c/(0.287 \text{ kJ/kg-K})(780 \text{ K}) = 11.011 V_c$$

mass in crevice volume

$$m_c = (2465 \text{ kPa})(0.025 V_c)/(0.287 \text{ kJ/kg-K})(463 \text{ K}) = 0.464 V_c$$

percent of mass in crevice

$$\% = \{(0.464 V_c)/[(0.464 V_c) + (11.011 V_c)]\}(100) = \underline{4.04\%}$$

(b) Eq. (3-11)

$$Q_{HV}\eta_i = (AF + 1)c_v(T_3 - T_2)$$

$$(43,000 \text{ kJ/kg})(1.0) = (14.6 + 1)(0.821 \text{ kJ/kg-K})(T_3 - 780 \text{ K})$$

$$T_3 = 4137 \text{ K}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (2465 \text{ kPa})(4137/780) = 13,074 \text{ kPa}$$

mass in clearance volume

$$m_{cc} = (13,074 \text{ kPa})V_c/(0.287 \text{ kJ/kg-K})(4137 \text{ K}) = 11.011 V_c$$

mass in crevice volume

$$m_c = (13,074 \text{ kPa})(0.025 V_c)/(0.287 \text{ kJ/kg-K})(463 \text{ K}) = 2.460 V_c$$

percent of mass in crevice

$$\% = \{(2.460 V_c)/[(2.460 V_c) + (11.011 V_c)]\}(100) = \underline{18.3\%}$$

(6-7)

(a)

for 1 cylinder $V_d = 6.8/8 = 0.85 \text{ L} = 0.00085 \text{ m}^3$

use Eq. (2-12) to find clearance volume of 1 cylinder

$$r_c = 18.5 = (V_d + V_c)/V_c = (0.00085 + V_c)/V_c$$

$$V_c = 0.00004857 \text{ m}^3 = 48.57 \text{ cm}^3$$

$$V_{\text{crevice}} = (0.03)(0.00004857 \text{ m}^3) = 1.46 \times 10^{-6} \text{ m}^3 = \underline{1.46 \text{ cm}^3}$$

(b)

Eqs. (3-52) and (3-53) and Fig. 3-11

$$T_2 = T_1(r_c)^{k-1} = (348 \text{ K})(18.5)^{0.35} = 966 \text{ K}$$

$$P_2 = P_1(r_c)^k = (120 \text{ kPa})(18.5)^{1.35} = 6164 \text{ kPa}$$

$P_2 < P_{\text{peak}}$ which means engine is operating on Dual cycle and not on Diesel cycle

mass in combustion chamber after compression (clearance volume)

$$m = PV/RT = (6164 \text{ kPa})V_c/(0.287 \text{ kJ/kg-K})(966 \text{ K}) = 22.233 V_c$$

mass in crevice volume

$$m = (6164 \text{ kPa})(0.03 V_c)/(0.287 \text{ kJ/kg-K})(463 \text{ K}) = 1.392 V_c$$

percent of mass in crevice

$$\% = \{(1.392 V_c)/[(1.392 V_c) + (22.233 V_c)]\}(100) = \underline{5.89\%}$$

(c)

$$P_x = P_{\text{peak}} = 11,000 \text{ kPa} \quad \text{given}$$

at constant volume

$$T_x = T_2(P_x/P_2) = (966 \text{ K})(11,000/6164) = 1724 \text{ K}$$

Eq. (3-85)

$$T_3 = \beta T_x = (2.3)(1724 \text{ K}) = 3965 \text{ K}$$

$$P_3 = P_x = 11,000 \text{ kPa}$$

mass in combustion chamber at end of combustion

$$m = (11,000 \text{ kPa})(2.3 V_c)/(0.287 \text{ kJ/kg-K})(3965 \text{ K}) = 22.233 V_c$$

mass in crevice volume at end of combustion

$$m = (11,000 \text{ kPa})(0.03 V_c)/(0.287 \text{ kJ/kg-K})(463 \text{ K}) = 2.483 V_c$$

percent of mass in crevice

$$\% = \{(2.483 V_c)/[(2.483 V_c) + (22.233 V_c)]\}(100) = \underline{10.05\%}$$

(6-8)

- (a) engine speed in degrees/sec
 $(1800/60 \text{ rev/sec})(360^\circ/\text{rev}) = 10,800 \text{ degrees/sec}$

$$22^\circ \text{ bTDC to } 4^\circ \text{ aTDC} = 26^\circ/\text{injection}$$

$$\text{time} \quad t = (26^\circ/\text{injection})/(10,800 \text{ degrees/sec}) = \underline{0.0024 \text{ sec/injection}}$$

- (b) Eq. (6-1)

$$(\text{SR})_1 = 2.8 = \omega/N = \omega/(1800/60 \text{ rev/sec}) \quad \omega = 84 \text{ rev/sec}$$

$$\text{period of swirl} = 1/\omega = 1/(84 \text{ rev/sec}) = \underline{0.012 \text{ sec/rev}}$$

- (c) Eq. (6-5)

$$\text{injection time} = (\text{period of swirl})/(\text{number of holes})$$

$$0.0024 = 0.012/(\text{number of holes}) \quad \underline{\text{number of holes} = 5 \text{ holes}}$$

(6-9)

- (a) for 1 cylinder $V_d = 2.6/4 = 0.65 \text{ L} = 0.00065 \text{ m}^3$

Eq. (2-12)

$$r_c = 10.5 = (V_d + V_c)/V_c = (0.00065 + V_c)/V_c \quad V_c = 0.0000684 \text{ m}^3$$

$$\text{volume of secondary chamber} \quad V_2 = (0.18)(0.0000684 \text{ m}^3) = 0.0000123 \text{ m}^3$$

$$\text{volume of primary chamber} \quad V_1 = 0.0000684 - 0.0000123 = 0.0000561 \text{ m}^3$$

in secondary chamber

$$m_2 = PV/RT = (2100 \text{ kPa})(0.0000123 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(700 \text{ K}) \\ = 0.000129 \text{ kg} = m_{a2} + m_n = (\text{AF} + 1)m_n = (13.2 + 1)m_n$$

$$m_n = 0.00000908 \text{ kg}$$

$$m_{a2} = (13.2)(0.00000908 \text{ kg}) = 0.0001200 \text{ kg}$$

in primary chamber

$$m_1 = PV/RT = (2100 \text{ kPa})(0.0000561 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(700 \text{ K}) \\ = 0.000586 \text{ kg} = m_{a1} + m_n = (\text{AF} + 1)m_n = (20.8 + 1)m_n$$

$$m_n = 0.0000269 \text{ kg}$$

$$m_{a1} = (20.8)(0.0000269 \text{ kg}) = 0.0005595 \text{ kg}$$

overall air-fuel ratio

$$\text{AF} = (m_{a1} + m_{a2})/(m_n + m_n) = (0.0005595 + 0.0001200)/(0.0000269 + 0.00000908) = \underline{18.9}$$

(b)

Eq. (3-11)

$$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2) \\ (43,000 \text{ kJ/kg})(0.98) = (13.2 + 1)(0.821 \text{ kJ/kg-K})(T_3 - 700 \text{ K})$$

$$T_3 = 4315 \text{ K} = \underline{4042^\circ \text{C}}$$

at constant volume

$$P_3 = P_2(T_3/T_2) = (2100 \text{ kPa})(4315/700) = \underline{12,945 \text{ kPa}}$$

(c)

mass in secondary chamber before expansion = 0.000129 kg

mass in secondary chamber after expansion (approximate)

$$m = PV/RT = (2100 \text{ kPa})(0.0000123 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(4315 \text{ K}) = 0.0000209 \text{ kg}$$

amount of mass through orifice during expansion

$$\Delta m = 0.000129 - 0.0000209 = 0.000108 \text{ kg}$$

expansion takes 7° of engine rotation, so time of expansion

$$t = (7/360 \text{ rev})/(2600/60 \text{ rev/sec}) = 0.000449 \text{ sec}$$

mass flow rate

$$\dot{m} = (0.000108 \text{ kg})/(0.000449 \text{ sec}) = 0.241 \text{ kg/sec} = \rho(\text{Vel})A$$

$$\text{density } \rho = P/RT = (12,945 \text{ kPa})/(0.287 \text{ kJ/kg-K})(4315 \text{ K}) = 10.45 \text{ kg/m}^3$$

$$\text{velocity Vel} = \dot{m}/\rho A = (0.241 \text{ kg/sec})/[(10.45 \text{ kg/m}^3)(0.0001 \text{ m}^2)]$$

$$\underline{\text{Vel} = 231 \text{ m/sec}}$$

CHAPTER 7

(7-1)

(a)

flame travel distance = bore/2 + offset

$$D_f = (10.2 \text{ cm})/2 + 0.6 \text{ cm} = 5.7 \text{ cm} = 0.057 \text{ m}$$

$$\text{time} = D_f / (\text{Vel})_f = (0.057 \text{ m}) / (15.8 \text{ m/sec}) = \underline{0.0036 \text{ sec}}$$

(b)

combustion starts at 13.5° bTDC

time of combustion in degrees of engine rotation

$$(0.0036 \text{ sec})(1200/60 \text{ rev/sec})(360^\circ/\text{rev}) = 25.9^\circ$$

crank position at end of combustion

$$25.9^\circ - 13.5^\circ = \underline{12.4^\circ \text{ aTDC}}$$

(7-2)

(a)

$$(\text{Vel})_{2000} = (0.92)(2000/1200)(15.8 \text{ m/sec}) = \underline{24.23 \text{ m/sec}}$$

(b)

real time of combustion development

$$t = (6.5^\circ) / [(360^\circ/\text{rev})(1200/60 \text{ rev/sec})] = 0.00090 \text{ sec}$$

time of combustion at 2000 RPM

$$t = D_f / (\text{Vel})_f = (0.057 \text{ m}) / (24.23 \text{ m/sec}) = 0.00235 \text{ sec}$$

total time of ignition and combustion at 2000 RPM

$$t = (0.00090 \text{ sec}) + (0.00235 \text{ sec}) = 0.00325 \text{ sec}$$

total time in degrees of engine rotation

$$(0.00325 \text{ sec})(2000/60 \text{ rev/sec})(360^\circ/\text{rev}) = 39.0^\circ$$

for combustion to end at 12.4° aTDC, spark plug must be fired

$$39.0^\circ - 12.4^\circ = \underline{26.6^\circ \text{ bTDC}}$$

(c)

engine rotation during combustion

$$(0.00235 \text{ sec})(2000/60 \text{ rev/sec})(360^\circ/\text{rev}) = 28.2^\circ$$

combustion must start

$$28.2^\circ - 12.4^\circ = \underline{15.8^\circ \text{ bTDC}}$$

(7-3)

- (a) Ignition delay of first fuel injected = 8° of rotation
 $t = (8^\circ)/[(360^\circ/\text{rev})(1850/60 \text{ rev/sec})] = \underline{0.00072 \text{ sec}}$

- (b) $16^\circ - 8^\circ = 8^\circ$ from problem statement

- (c) ignition delay is half of original ID
 $ID = (0.00072 \text{ sec})/2 = 0.00036 \text{ sec}$

time between start of Injection and final Ignition of last fuel droplets
 $t = (0.0019 \text{ sec}) + (0.00036 \text{ sec}) = 0.00226 \text{ sec}$

in degrees of engine rotation $(0.00226 \text{ sec})(1850/60 \text{ rev/sec})(360^\circ/\text{rev}) = 25.1^\circ$
crank position when last droplets start to combust $16^\circ \text{ bTDC} + 25.1^\circ = \underline{9.1^\circ \text{ aTDC}}$

(7-4)

- (a) using Eq. (2-8) for 1 cylinder of a 4 cylinder engine
 $V_d = (3.2 \text{ L})/4 = 0.8 \text{ L} = 0.0008 \text{ m}^3 = (\pi/4)B^2S = (\pi/4)(0.95)B^3$
 $B = 0.10235 \text{ m} \quad S = (0.95)(0.10235 \text{ m}) = 0.0972 \text{ m}$

use Eq. (2-2) to find engine speed
 $\bar{U}_p = 8 \text{ m/sec} = 2SN = (2 \text{ strokes/rev})(0.0972 \text{ m/stroke})N$
 $N = 41.15 \text{ rev/sec} = 2469 \text{ RPM}$

time of flame $t = (25^\circ)/[(360^\circ/\text{rev})(41.15 \text{ rev/sec})] = 0.00169 \text{ sec}$
distance of flame travel $D_f = B/4 = (0.10235 \text{ m})/4 = 0.02559 \text{ m}$
flame speed $(\text{Vel})_f = D_f/t = (0.02559 \text{ m})/(0.00169 \text{ sec}) = \underline{15.15 \text{ m/sec}}$

- (b) using Eq. (2-8) for 1 cylinder of V8 engine
 $V_d = (3.2 \text{ L})/8 = 0.4 \text{ L} = 0.0004 \text{ m}^3 = (\pi/4)B^2S = (\pi/4)(0.95)B^3$
 $B = 0.08124 \text{ m} \quad S = (0.95)(0.08124 \text{ m}) = 0.07718 \text{ m}$

use Eq. (2-2) to find engine speed
 $\bar{U}_p = 8 \text{ m/sec} = 2SN = (2 \text{ strokes/rev})(0.07718 \text{ m/stroke})N$
 $N = 51.83 \text{ rev/sec} = 3110 \text{ RPM}$

time of flame $t = (25^\circ)/[(360^\circ/\text{rev})(51.83 \text{ rev/sec})] = 0.00134 \text{ sec}$
distance of flame travel $D_f = B/4 = (0.08124 \text{ m})/4 = 0.02031 \text{ m}$
flame velocity $(\text{Vel})_f = D_f/t = (0.02031 \text{ m})/(0.00134 \text{ sec}) = \underline{15.15 \text{ m/sec}}$

flame speeds for both engines are the same !!

(7-5)

(a) $ID = (0.0065 \text{ sec})(310/60 \text{ rev/sec})(360^\circ/\text{rev}) = \underline{12.1^\circ}$

(b) $21^\circ \text{ bTDC} + 12.1^\circ = \underline{8.9^\circ \text{ bTDC}}$

(c) engine rotation per injection $(0.019 \text{ sec})(310/60 \text{ rev/sec})(360^\circ/\text{rev}) = 35.3^\circ/\text{injection}$
crank position $21^\circ \text{ bTDC} + 35.3^\circ = \underline{14.3^\circ \text{ aTDC}}$

(7-6)

Advantages:

shorter flame travel distance - closer to constant volume combustion
(higher real thermal efficiency)

less chance of knock

less chance of poor ignition or misfire

Disadvantages:

hard to fit valves and spark plugs into combustion chamber

cost

need for more complex ignition system

(7-7)

(a) actual total fuel $m_f = m_{f1} + m_{f2}$

actual overall fuel-air ratio $(FA)_{act} m_a = (FA)_1 m_{a1} + (FA)_2 m_{a2}$
 $(FA)_{act} = [(FA)_1 m_{a1} + (FA)_2 m_{a2}] / m_a$

equivalence ratio using Eq. (2-57)

$$\begin{aligned}\phi &= (FA)_{act} / (FA)_{stoich} = [(FA)_1 m_{a1} + (FA)_2 m_{a2}] / [m_a (FA)_{stoich}] \\ &= (\phi_1 m_{a1} + \phi_2 m_{a2}) / m_a = \phi_1 (m_{a1} / m_a) + \phi_2 (m_{a2} / m_a) = \phi_1 (\text{volume } \%)_1 + \phi_2 (\text{volume } \%)_2 \\ &= (1.2)(0.22) + (0.75)(0.78) = 0.849\end{aligned}$$

Eq. (2-57)

$$(AF)_{act} = (AF)_{stoich} / \phi = 14.6 / 0.849 = \underline{17.2}$$

(b) $\phi = \underline{0.849}$ from above

(7-8)

- (a) use Eq. (2-71) for air flow rate into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.002)(0.92)(3500/60)/2 = 0.06338 \text{ kg/sec}$$

Eq. (2-55) for fuel flow rate

$$\dot{m}_f = \dot{m}_a / (AF) = (0.06338 \text{ kg/sec})/17.2 = 0.003685 \text{ kg/sec}$$

Eq. (2-64)

$$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (0.003685 \text{ kg/sec})(43,000 \text{ kJ/kg})(0.99) = 156.87 \text{ kJ/sec}$$

using Eqs. (2-47) and (2-65)

$$\dot{W}_b = \eta_t \dot{Q}_{in} \eta_m = (0.52)(156.87 \text{ kJ/sec})(0.86) = \underline{70.15 \text{ kW}}$$

- (b) Eq. (2-88) bmep = $(1000)(70.15)(2)/(2)(3500/60) = \underline{1203 \text{ kPa}}$

- (c) unburned fuel

$$(\dot{m}_f)_{unburned} = \dot{m}_f (1 - \eta_c) = (0.003685 \text{ kg/sec})(1 - 0.99)(3600 \text{ sec/hr}) = \underline{0.133 \text{ kg/hr}}$$

- (d) Eq. (2-60)

$$bsfc = \dot{m}_f / \dot{W}_b = (3.685 \text{ gm/sec})(3600 \text{ sec/hr})/(70.15 \text{ kW}) = \underline{189 \text{ gm/kW-hr}}$$

(7-9)

- (a) use Eq. (2-71) for air flow rate into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.002)(0.93)(3500/60)/2 = 0.06407 \text{ kg/sec}$$

Eq. (2-55) for fuel flow rate

$$\dot{m}_f = \dot{m}_a / (AF) = (0.06407 \text{ kg/sec})/14.6 = 0.004388 \text{ kg/sec}$$

Eq. (2-64)

$$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (0.004388 \text{ kg/sec})(43,000 \text{ kJ/kg})(0.98) = 184.9 \text{ kJ/sec}$$

using Eqs. (2-47) and (2-65)

$$\dot{W}_b = \eta_t \dot{Q}_{in} \eta_m = (0.47)(184.9 \text{ kJ/sec})(0.86) = \underline{74.74 \text{ kW}}$$

- (b) Eq. (2-88) bmep = $(1000)(74.74)(2)/(2)(3500/60) = \underline{1281 \text{ kPa}}$

- (c) unburned fuel

$$(\dot{m}_f)_{unburned} = \dot{m}_f (1 - \eta_c) = (0.004388 \text{ kg/sec})(1 - 0.98)(3600 \text{ sec/hr}) = \underline{0.316 \text{ kg/hr}}$$

- (d) Eq. (2-60)

$$bsfc = \dot{m}_f / \dot{W}_b = (4.388 \text{ gm/sec})(3600 \text{ sec/hr})/(74.74 \text{ kW}) = \underline{211 \text{ gm/kW-hr}}$$

(7-10)

(a) $\angle = (10^\circ \text{ bTDC}) - (20^\circ \text{ bTDC}) = \underline{10^\circ}$

(b) $t = (10^\circ) / [(2400/60 \text{ rev/sec})(360^\circ/\text{rev})] = \underline{0.000694 \text{ sec}}$

(c) angle turned during flame propagation

$\angle = (2400/60 \text{ rev/sec})(360^\circ/\text{rev})(0.001667 \text{ sec}) = 24^\circ$

final crank angle

$\angle = (10^\circ \text{ bTDC}) + (24^\circ) = \underline{14^\circ \text{ aTDC}}$

(7-11)

(a) angle turned during flame development

$\angle = (1200/60 \text{ rev/sec})(360^\circ/\text{rev})(0.00125 \text{ sec}) = 9^\circ$

angle when flame propagation starts

$\angle = (19^\circ \text{ bTDC}) + (9^\circ) = \underline{10^\circ \text{ bTDC}}$

(b) time of flame propagation

$t = (0.12 \text{ m}) / (48 \text{ m/sec}) = 0.0025 \text{ sec}$

angle of flame propagation

$\angle = (1200/60 \text{ rev/sec})(360^\circ/\text{rev})(0.0025 \text{ sec}) = 18^\circ$

angle when flame propagation ends

$\angle = (10^\circ \text{ bTDC}) + (18^\circ) = \underline{8^\circ \text{ aTDC}}$

(c) flame speed at 2400 RPM

$u_f = (0.80)(2400/1200)(48 \text{ m/sec}) = 76.8 \text{ m/sec}$

angle turned during flame propagation

$\angle = [(0.12 \text{ m}) / (76.8 \text{ m/sec})] (2400/60 \text{ rev/sec})(360^\circ/\text{rev}) = 22.5^\circ$

angle when spark plug should be fired

$\angle = (8^\circ \text{ aTDC}) - (22.5^\circ) = \underline{14.5^\circ \text{ bTDC}}$

(d) Eq.(2-2) gives average piston speed

$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.35 \text{ m/stroke})(1200/60 \text{ rev/sec}) = 14.0 \text{ m/sec}$

Eq.(2-5)

$\bar{U}_p / \bar{U}_p = (\pi/2) \sin \theta [1 + (\cos \theta / \sqrt{R^2 - \sin^2 \theta})]$

$= (\pi/2) \sin(8^\circ) [1 + (\cos(8^\circ) / \sqrt{(4.23)^2 - \sin^2(8^\circ)})] = 0.2698$

$\bar{U}_p = (0.2698) \bar{U}_p = (0.2698)(14.0 \text{ m/sec}) = \underline{3.78 \text{ m/sec}}$

(e) Eq.(2-8) gives displacement volume of one cylinder

$V_d = (\pi/4) B^2 S = (\pi/4) (0.24 \text{ m})^2 (0.35 \text{ m}) = 0.01583 \text{ m}^3$

Eq.(2-12) gives clearance volume

$r_c = (V_c + V_d) / V_c = 8.2 = (V_c + 0.01583) / V_c$

$V_c = 0.002199 \text{ m}^3$

Eq.(2-14)

$V/V_c = 1 + \frac{1}{2} (r_c - 1) [R + 1 - \cos \theta - \sqrt{R^2 - \sin^2 \theta}]$

$= (1) + (\frac{1}{2}) (8.2 - 1) [(4.23) + (1) - \cos(8^\circ) - \sqrt{(4.23)^2 - \sin^2(8^\circ)}] = 1.044$

$V = (1.044) V_c = (1.044) (0.002199 \text{ m}^3) = \underline{0.00229 \text{ m}^3} = 2.29 \text{ L}$

(7-12)

(a)

Eq. (3-31)

high-load

low-load

$$\eta_t = 1 - (1/r_c)^{1-k} = 1 - (1/8.4)^{1-1.35} = 0.525 = 52.5\%$$
$$\eta_t = 1 - (1/13.7)^{1-1.35} = 0.600 = 60.0\%$$

(b)

Eq. (2-71) gives air flow in at high-load

$$\dot{m}_a = \eta_v \rho_a V_d N/n$$
$$= 1.20 (.0739 \text{ lbm/ft}^3) [(380)/(12)^3 \text{ ft}^3/\text{cycle}] (3200/60 \text{ rev/sec}) / 2 \text{ rev/cycle}$$
$$= 0.5200 \text{ lbm/sec}$$

Eq. (2-55) gives fuel flow at high-load

$$\dot{m}_f = \dot{m}_a / AF = (0.5200 \text{ lbm/sec}) / (13.5) = 0.0385 \text{ lbm/sec}$$

at low-load

$$\dot{m}_a = (.78) (.0739 \text{ lbm/ft}^3) [(380)/(12)^3 \text{ ft}^3/\text{cycle}] (2100/60 \text{ rev/sec}) / 2$$
$$= 0.2218 \text{ lbm/sec}$$
$$\dot{m}_f = (0.2218 \text{ lbm/sec}) / (22) = 0.01008 \text{ lbm/sec}$$

(c)

Eq. (2-65) gives indicated power at high-load

$$\dot{W} = \eta_t \dot{m}_f Q_{HV} \eta_c$$
$$= .525 (.0385 \text{ lbm/sec}) (43000 \text{ kJ/kg}) (.4299 \text{ BTU/lbm/kJ/kg}) (.94) (3600 \text{ sec/hr})$$
$$= 1,264,000 \text{ BTU/hr}$$
$$\dot{W} = (1,264,000 \text{ BTU/hr}) / (2545 \text{ BTU/hr/hp}) = 497 \text{ hp}$$

at low-load

$$\dot{W} = (0.600) (0.01008) [(43,000) (0.4299)] (0.99) (3600) / (2545)$$
$$= 157 \text{ hp}$$

(d)

high-load

$$\text{isfc} = (.0385 \text{ lbm/sec}) (3600 \text{ sec/hr}) / (497 \text{ hp}) = 279 \text{ lbm/hp-hr}$$

low-load

$$\text{isfc} = (0.1008 \text{ lbm/sec}) (3600 \text{ sec/hr}) / (157 \text{ hp}) = 231 \text{ lbm/hp-hr}$$

CHAPTER 8

(8-1)

(a)

Eq. (8-3) and Fig. 8-1

$$T_{ex} = T_7 = T_4(P_7/P_4)^{(k-1)/k} = (1000 \text{ K})(100/520)^{(1.35-1)/1.35} = 652 \text{ K} = \underline{379^\circ \text{ C}}$$

(b)

Eq. (3-46)

$$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/8.5)(1000/652)(100/520) = 0.035 = \underline{3.5\%}$$

(c)

Eq. (3-50)

$$(T_m)_1 = x_r T_{ex} + (1 - x_r) T_a = (0.035)(652 \text{ K}) + (1 - 0.035)(308 \text{ K}) = 320 \text{ K} = \underline{47^\circ \text{ C}}$$

(d)

$$\begin{aligned} \text{Eq. (3-16)} \quad T_4 &= 1000 \text{ K} = T_3(1/r_c)^{k-1} = T_3(1/8.5)^{0.35} \\ T_3 &= 2115 \text{ K} = \underline{1842^\circ \text{ C}} \end{aligned}$$

(e)

$$T_{IVO} = T_{ex} = \underline{379^\circ \text{ C}} \quad \text{from above}$$

(8-2)

(a)

Eq. (8-3) and Fig. 8-1

$$T_{ex} = T_7 = T_{EVO}(P_{ex}/P_{EVO})^{(k-1)/k} = (3220 \text{ R})(14.6/70)^{(1.35-1)/1.35} = 2145^\circ \text{ R} = \underline{1685^\circ \text{ F}}$$

(b)

Eq. (3-46)

$$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9)(3220/2145)(14.6/70) = 0.035 = \underline{3.5\%}$$

(c)

exhaust residual will be cooled by expansion cooling when intake valve opens

temperature of exhaust residual after intake valve opens

$$T_{xr} = T_{ex}(T_{intake}/T_{ex})^{(k-1)/k} = (2145^\circ \text{ R})(8.8/14.6)^{(1.35-1)/1.35} = 1881^\circ \text{ R}$$

Eq. (3-50)

$$(T_m)_1 = x_r T_{xr} + (1 - x_r) T_a = (0.035)(1881^\circ \text{ R}) + (1 - 0.035)(595^\circ \text{ R}) = 640^\circ \text{ R} = \underline{180^\circ \text{ F}}$$

$$\underline{P_1 = 8.8 \text{ psia}} \quad \text{given}$$

(8-3)

(a)

Eq. (3-1h) and Fig. 3-16

$$P_2 = P_1(T_2/T_1)^{k/(k-1)} = (9000 \text{ kPa})(1548/3173)^{1.35/(1.35-1)} = \underline{565 \text{ kPa}}$$

(b)

sonic velocity using Eq. (3-1j)

$$Vel = c = [kRT]^{1/2} = [(1.35)(287 \text{ J/kg}\cdot\text{K})(1548 \text{ K})(1 \text{ kg}\cdot\text{m/N}\cdot\text{sec}^2)]^{1/2} = \underline{774 \text{ m/sec}}$$

(8-4)

Otto cycle engine

Eq. (3-16) and Fig. 3-2

$$T_{Evo} = T_4 = T_3(1/r_c)^{k-1} = (2400 \text{ K})(1/8.5)^{0.35} = 1135 \text{ K} = \underline{862^\circ \text{C}}$$

Diesel cycle engine

Eq. (3-62) and Fig. 3-8

$$\beta = V_3/V_2 \quad V_3 = \beta V_2$$

Eqs. (3-64) and (2-12)

$$\begin{aligned} T_4 &= T_3(V_3/V_2)^{k-1} = T_3(\beta V_2/V_2)^{k-1} = T_3(\beta/r_c)^{k-1} = (2400 \text{ K})(1.95/20.5)^{0.35} \\ &= 1053 \text{ K} = \underline{780^\circ \text{C}} \end{aligned}$$

(8-5)

- 1) There is a larger pressure differential pushing the essentially same mass amount through the exhaust valve.
- 2) When choked flow occurs, sonic velocity through the exhaust valve is greater due to the higher temperature.

(8-6)

(a) use Fig. 8-1

exhaust blowdown lasts for 56° of engine rotation

$$\text{time } t = (56^\circ)/[(4500/60 \text{ rev/sec})(360^\circ/\text{rev})] = \underline{0.0021 \text{ sec}}$$

(b) Eqs. (3-16) and (3-17)

$$T_4 = T_3(1/r_c)^{k-1} = (2700 \text{ K})(1/10.1)^{0.35} = 1202 \text{ K}$$

$$P_4 = P_3(1/r_c)^k = (8200 \text{ kPa})(1/10.1)^{1.35} = 361 \text{ kPa}$$

$$\text{for 1 cylinder } V_d = (1.8 \text{ L})/3 = 0.6 \text{ L} = 0.0006 \text{ m}^3$$

Eq. (2-12)

$$r_c = 10.1 = (V_d + V_c)/V_c = (0.0006 + V_c)/V_c \quad V_c = 0.0000659 \text{ m}^3$$

Eq. (2-11)

$$V_{\text{BDC}} = V_c + V_d = 0.0000659 + 0.0006 = 0.0006659 \text{ m}^3$$

$$m_{\text{EVO}} = m_4 = P_4 V_4 / RT_4 = (361 \text{ kPa})(0.0006659 \text{ m}^3) / (0.287 \text{ kJ/kg-K})(1202 \text{ K}) \\ = 0.000697 \text{ kg} \quad \text{at start of blowdown}$$

after blowdown at state 7

$$P_7 = P_{\text{ex}} = 98 \text{ kPa} \quad V = V_{\text{BDC}} = 0.0006659 \text{ m}^3$$

Eq. (3-37)

$$T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2700 \text{ K})(98/8200)^{(1.35-1)/1.35} = 857 \text{ K} = T_{\text{ex}}$$

$$m = PV/RT = (98)(0.0006659)/(0.287)(857) = 0.000265 \text{ kg}$$

mass that exits cylinder during blowdown

$$\Delta m = (0.000697 \text{ kg}) - (0.000265 \text{ kg}) = 0.000432 \text{ kg}$$

$$\% \Delta = [(0.000432)/(0.000697)](100) = \underline{62.0\%}$$

(c) Eq. (2-8) to find stroke length

$$V_d = (\pi/4)B^2S = 600 \text{ cm}^3 = (\pi/4)B^2(0.85B)$$

$$B = 9.65 \text{ cm} \quad S = (0.85)B = (0.85)(9.65 \text{ cm}) = 8.20 \text{ cm}$$

crankshaft offset

$$a = S/2 = (8.20 \text{ cm})/(2) = 4.10 \text{ cm}$$

$$R = r/a = (16.4 \text{ cm})/(4.10 \text{ cm}) = 4.0$$

Eq. (2-14) for volume when exhaust valve opens

$$V_{\text{EVO}}/V_c = 1 + \frac{1}{2}(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$$

$$= 1 + \frac{1}{2}(10.1 - 1)[(4) + (1) - \cos(124^\circ) - \sqrt{(4)^2 - \sin^2(124^\circ)}] = 8.490$$

$$T_{\text{EVO}} = T_3(V_3/V_{\text{EVO}})^{k-1} = T_c(V_c/V_{\text{EVO}})^{k-1} = (2700 \text{ K})(1/8.490)^{1.35-1} = 1277 \text{ K}$$

Eq. (3-1)(j) for sonic velocity

$$v = c = \sqrt{kRT} = [(1.35)(287 \text{ J/kg-K})(1277 \text{ K})(1 \text{ kg-m/N-sec}^2)]^{1/2} = \underline{703 \text{ m/sec}}$$

(8-7)

(a) pseudo steady state temperature

$$T_{ex} = T_7 = 857 \text{ K} = \underline{584^\circ \text{C}} \quad \text{from Prob. (6)}$$

(b) when velocity is dissipated, KE is changed to enthalpy increase

$$(Vel)^2/2g_c = \Delta h = c_p \Delta T$$

$$\Delta T = (Vel)^2/2g_c c_p \\ = (703 \text{ m/sec})^2 / [(2) (1 \text{ kg-m/N-sec}^2) (1.108 \text{ kJ/kg-K}) (1000 \text{ J/kJ})] = 223^\circ$$

$$T_{max} = (857) + (223) = \underline{1080 \text{ K} = 807^\circ \text{C}}$$

(8-8)

(a)

Eq. (3-37) and Fig. 8-1

$$T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2500 \text{ K})(101/6800)^{(1.35-1)/1.35} = 839 \text{ K} = \underline{566^\circ \text{C}}$$

(b)

Eqs. (3-16) and (3-17)

$$T_4 = T_3(1/r)^{k-1} = (2500 \text{ K})(1/9.6)^{0.35} = 1133 \text{ K}$$

$$P_4 = P_3(1/r)^k = (6800 \text{ kPa})(1/9.6)^{1.35} = 321 \text{ kPa}$$

Eq. (3-46)

$$x_r = (1/r)(T_4/T_{ex})(P_{ex}/P_4) = (1/9.6)(1133/839)(101/321) = 0.044 = \underline{4.4\%}$$

(c)

$$\text{total exhaust in cycle} = x_r + \text{EGR} = 4.4 + 12 = 16.4\%$$

temperature of exhaust after intake valve opens and expansion cooling occurs

$$T_{ex} = (839 \text{ K})(75/101)^{(1.35-1)/1.35} = 777 \text{ K}$$

Eq. (3-50)

$$T_1 = x_r T_{ex} + (1 - x_r) T_a = (0.164)(777 \text{ K}) + (1 - 0.164)(333 \text{ K}) = 406 \text{ K} = \underline{133^\circ \text{C}}$$

(d)

temperature of flow through intake valve with 12% EGR added to inlet air

Eq. (3-50)

$$T_i = (0.12)(777 \text{ K}) + (1 - 0.12)(333 \text{ K}) = 386 \text{ K}$$

$$\text{Eq. (8-6)} \quad \alpha = A_{ex}/A_i = (T_i/T_{ex})^{1/2} = (386/839)^{1/2} = 0.678 = [(\pi/4)d_{ex}^2]/[(\pi/4)d_i^2]$$

$$d_{ex}/d_i = (0.678)^{1/2} = \underline{0.82}$$

(8-9)

(a) time of blowdown

$$t = (48^\circ) / [(3200/60 \text{ rev/sec})(360^\circ/\text{rev})] = \underline{0.0025 \text{ sec}}$$

(b) using Fig. 8-1 and Eq. (3-37)

$$T_{\text{ex}} = T_7 = T_{\text{max}} (P_{\text{ex}}/P_{\text{max}})^{k-1/k} = (2800\text{K}) (100/6500)^{1.35-1/1.35} = \underline{949 \text{ K} = 676^\circ\text{C}}$$

(c) temperature when exhaust valve opens

$$T_{\text{EVO}} = T_4 = T_{\text{max}} (P_{\text{EVO}}/P_{\text{max}})^{k-1/k} = (2800\text{K}) (100/6500)^{1.35-1/1.35} = 1462 \text{ K}$$

choked flow will be sonic, using eq (3-1)(j)

$$u_{\text{ex}} = c = \sqrt{kRT} = \sqrt{(1.35)(0.287\text{kJ/kg-K})(1462\text{K})(1\text{kg-m/N-sec}^2)(1000\text{J/kJ})} \\ = \underline{753 \text{ m/sec}}$$

(8-10)

(a) using Fig. 8-1 and eq (3-37)

$$T_{\text{ex}} = T_7 = T_{\text{max}} (P_{\text{ex}}/P_{\text{max}})^{k-1/k} = (3100\text{K}) (101/7846)^{1.35-1/1.35} = \underline{1003 \text{ K} = 730^\circ\text{C}}$$

(b) cylinder volume at TDC

$$V_3 = mRT/P = (0.000622\text{kg})(0.287\text{kJ/kg-K})(3100\text{K})/(7846\text{kPa}) = 0.0000705\text{m}^3$$

cylinder volume when exhaust valve opens

$$V_{\text{EVO}} = V_4 = V_3/r_c = (0.0000705 \text{ m}^3)/(9.8) = 0.000691 \text{ m}^3$$

cylinder mass at end of blowdown

$$m_{\text{ex}} = P_{\text{ex}} V_4 / RT_{\text{ex}} = (101\text{kPa})(0.000691\text{m}^3)/(0.287\text{kJ/kg-K})(1003\text{K}) \\ = \underline{0.000242 \text{ kg}}$$

(c) mass of one blowdown process in one cylinder

$$\Delta m = m_3 - m_{\text{ex}} = (0.000622 \text{ kg}) - (0.000242 \text{ kg}) = 0.000380 \text{ kg}$$

time valve must be open

$$t = (0.000380 \text{ kg})/(0.218 \text{ kg/sec}) = 0.00174 \text{ sec}$$

crank angle of blowdown

$$\angle = (3800/60 \text{ rev/sec})(360^\circ)(0.00174 \text{ sec}) = 39.7^\circ \\ \text{open exhaust valve at } \underline{39.7^\circ \text{ bBDC}}$$

(8-11)

(a)

use Eq. (2-71) for mass flow rate of air into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0056)(0.90)(2800/60)/2 = 0.1389 \text{ kg/sec}$$

total exhaust flow = air flow + fuel flow

$$\dot{m}_{\text{ex}} = (\dot{m}_a + \dot{m}_f) = \dot{m}_a(1 + \text{FA}) = (0.1389 \text{ kg/sec})(1 + 0.068) = \underline{0.148 \text{ kg/sec}}$$

(b)

Eq. (8-9)

$$\dot{W}_t = \dot{m} c_p \Delta T = (0.148 \text{ kg/sec})(1.108 \text{ kJ/kg-K})(44^\circ) = \underline{7.22 \text{ kW}}$$

(8-12)

(a)

density of air entering compressor

$$\rho = P/RT = (96 \text{ kPa})/(0.287 \text{ kJ/kg}\cdot\text{K})(300 \text{ K}) = 1.115 \text{ kg/m}^3$$

use Eq. (2-70) for mass flow of air through compressor

$$\dot{m}_a = \rho_a V_a \eta_r N/n = (1.115)(0.0015)(1.08)(2400/60)/2 = \underline{0.0361 \text{ kg/sec}}$$

(b)

mass flow rate of exhaust through turbine = air flow rate + fuel flow rate

$$\dot{m}_{ex} = (\dot{m}_a + \dot{m}_f) = \dot{m}_a(1 + FA) = (0.0361 \text{ kg/sec})(1 + 0.068) = \underline{0.0386 \text{ kg/sec}}$$

(c)

power needed for compressor using low temperature values of k and c_p

Eq. (5-15) gives T_{out} if compressor is isentropic

$$T_{2s} = T_1(P_2/P_1)^{(k-1)/k} = (300 \text{ K})(120/96)^{(1.40-1)/1.40} = 320 \text{ K}$$

Eq. (5-13) for isentropic power needed to drive compressor

$$\begin{aligned}(\dot{W}_s)_{comp} &= \dot{m}_a(h_{out} - h_{in}) = \dot{m}_a c_p(T_{out} - T_{in}) \\ &= (0.0361 \text{ kg/sec})(1.005 \text{ kJ/kg}\cdot\text{K})(320 - 300)\text{K} = 0.726 \text{ kW}\end{aligned}$$

actual power to drive compressor using Eq. (5-14)

$$(\dot{W}_{act})_{comp} = (\dot{W}_s)_{comp}/\eta_s = (0.726 \text{ kW})/0.78 = 0.931 \text{ kW}$$

Eq. (5-13) for actual air temperature at compressor exit

$$\begin{aligned}(\dot{W}_{act})_{comp} &= \dot{m}_a c_p(T_{out} - T_{in}) = 0.931 \text{ kW} = (0.0361 \text{ kg/sec})(1.005 \text{ kJ/kg}\cdot\text{K})(T_{out} - 300 \text{ K}) \\ T_{out} &= 326 \text{ K} = \underline{53^\circ \text{C}}\end{aligned}$$

(d)

exit temperature if turbine is isentropic

$$(T_{out})_s = T_{in}(P_{out}/P_{in})^{(k-1)/k} = (770 \text{ K})(98/119)^{(1.35-1)/1.35} = 732 \text{ K}$$

isentropic power from turbine

$$\begin{aligned}(\dot{W}_s)_{turb} &= \dot{m}_{ex}(h_{in} - h_{out}) = \dot{m}_{ex} c_p(T_{in} - T_{out}) \\ &= (0.0386 \text{ kg/sec})(1.108 \text{ kJ/kg}\cdot\text{K})(770 - 732)\text{K} = 1.625 \text{ kW}\end{aligned}$$

actual power from turbine

$$(\dot{W}_{act})_{turb} = \eta_s(\dot{W}_s)_{turb} = (1.625 \text{ kW})(0.80) = 1.30 \text{ kW}$$

$$\begin{aligned}(\dot{W}_{act})_{turb} &= \dot{m}_{ex} c_p(T_{in} - T_{out}) = 1.30 \text{ kW} = (0.0386 \text{ kg/sec})(1.108 \text{ kJ/kg}\cdot\text{K})(770 \text{ K} - T_{out}) \\ T_{out} &= 740 \text{ K} = \underline{467^\circ \text{C}}\end{aligned}$$

CHAPTER 9

(9-1)

1 kmole of $C_{12}H_{22}$ has 144 kg of carbon and 22 kg of hydrogen

mass % of carbon in fuel = $144/166 = 0.8675$

carbon put into atmosphere

$$\dot{m}_{\text{carbon}} = [(0.8675)(100 \text{ gm/mile})](15,000 \text{ miles/yr})(0.005) = 6500 \text{ gm/yr} = \underline{6.50 \text{ kg/yr}}$$

(9-2)

(a)

CI engines operate overall lean.

Exhaust temperature is lower on CI engines.

Solid carbon in exhaust requires larger flow passages.

(b)

Generation of NO_x is reduced by using EGR to lower combustion temperatures.

(c)

Less efficient combustion when EGR is used - more chance of slow combustion or misfire.

Lower combustion temperature gives lower cycle thermal efficiency.

Solid carbon in exhaust is abrasive on cylinder components and harmful to lubricating oil.

(9-3)

(a) 1) Not enough oxygen when engine operates fuel-rich.

2) Fuel gets trapped in crevice volume of cylinder.

3) Combustion is quenched in boundary layer of combustion chamber surface.

4) Intake fuel is exhausted during valve overlap.

5) Fuel vapor gets absorbed-desorbed in wall deposits.

6) Fuel vapor gets absorbed-desorbed in oil film on wall.

7) Poor combustion of oil in combustion chamber.

(b) Lean:

Engine generates lower HC and CO (Fig.9-1)

Slightly lean generates high NO_x (Fig.9-1)

Catalytic converter is inefficient for NO_x (Fig.9-11)

Stoichiometric:

Catalytic converter most efficient for all emissions (Fig.9-11)
High engine temperatures, so high generation of NO_x

Rich:

Engine generates high levels of HC and CO (Fig.9-1)

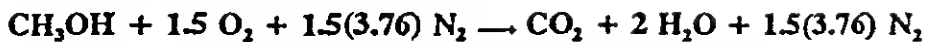
Catalytic converter is inefficient for all emissions (Fig.9-11)

(c) A major percentage of emissions getting exhausted to the environment occurs at engine startup when the catalytic converter is cold. If a catalytic converter is placed near the engine there is less heat loss before the converter and it will reach efficient operating temperature quicker. This would reduce overall emissions.

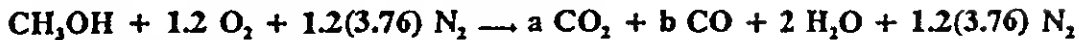
If a catalytic converter is placed near the engine in the engine compartment it is much more difficult to cool the engine compartment properly because the converter is hot and it restricts air flow. Modern automobile design allows for very small engine compartments with no room for a catalytic converter. A converter mounted in the engine compartment would have a higher steady state operating temperature which would result in quicker thermal degradation.

(9-4)

stoichiometric combustion reaction



combustion reaction with equivalence $\phi = 1.25$

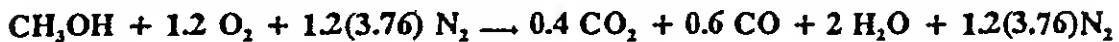


conservation of carbon $a + b = 1$

conservation of oxygen $2a + b + 2 = 3.4$

$$a = 0.4 \quad b = 0.6$$

actual combustion reaction



(a)

mole fraction of CO

$$x_{\text{CO}} = N_{\text{CO}}/N_{\text{total}} = (0.6)/[0.4 + 0.6 + 2 + 1.2(3.76)] = 0.0799 = \underline{7.99\%}$$

(b)

mass flow rate of air into engine using Eq. (2-71)

$$\begin{aligned} \dot{m}_a &= \rho_a \eta_v V_a N / n \\ &= (1.181 \text{ kg/m}^3) (0.885) (0.0028 \text{ m}^3/\text{cycle}) (2300/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ &= 0.0561 \text{ kg/sec} \end{aligned}$$

actual fuel-air ratio using Eq. (2-57)

$$(\text{FA})_a = \phi(\text{FA})_s = (1.25)(0.155) = 0.194$$

flow rate of fuel into engine using Eq. (2-56)

$$\begin{aligned} \dot{m}_f &= (\text{FA})_a \dot{m}_a = (0.194)(0.0561 \text{ kg/sec}) = 0.0109 \text{ kg/sec} \\ &= (0.0109 \text{ kg/sec}) / (32 \text{ kg/kgmole}) = 0.00034 \text{ kgmoles/sec} \end{aligned}$$

for every 1 mole of fuel there are 0.6 moles of CO in exhaust

CO in exhaust

$$\dot{m}_{\text{CO}} = (0.6)(0.00034 \text{ kgmoles/sec}) = 0.000204 \text{ kgmoles/sec}$$

$$\dot{Q}_{\text{lost}} = \dot{m}_{\text{CO}} Q_{\text{fiv}} = (0.000204 \text{ kgmoles/sec})(28 \text{ kg/kgmole})(10,100 \text{ kJ/kg}) = \underline{57.7 \text{ kW}}$$

(9-5)

(a)

displacement volume of 1 cylinder

$$V_d = (410 \text{ in.}^3)/8 = 51.25 \text{ in.}^3$$

use Eq. (2-12) to find clearance volume

$$r_c = 7.8 = (V_d + V_c)/V_c = (51.25 + V_c)/V_c$$
$$V_c = 7.537 \text{ in.}^3$$

at TDC when combustion occurs V_c = combustion chamber volume

$$V_c = 7.537 \text{ in.}^3 = (\pi/4)B^2h = (\pi/4)(3.98 \text{ in.})^2h$$

$$h = 0.606 \text{ in.} = \text{height of combustion chamber at TDC}$$

volume of boundary layer of thickness t

$$\text{side } V_{\text{side}} = \pi Bht = \pi(3.98)(0.606)(0.004) = 0.0303 \text{ in.}^3$$

$$\text{top } V_{\text{top}} = (\pi/4)B^2t = (\pi/4)(3.98)^2(0.004) = 0.0498 \text{ in.}^3$$

piston

$$\text{face } V_{\text{face}} = (\pi/4)B^2t = (\pi/4)(3.98)^2(0.004) = 0.0498 \text{ in.}^3$$

total volume of boundary layer

$$V_{\text{BL}} = (0.0303) + (0.0498) + (0.0498) = 0.130 \text{ in.}^3$$

$$\% \text{ of total volume} = 0.130/7.537 = 0.0172 = 1.72\%$$

$$\text{with fuel equally distributed} \quad \underline{\% \text{ fuel not burned} = 1.72\%}$$

(b)

use Eq. (2-70) for air flow rate into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n$$
$$= (0.0739 \text{ lbm/ft}^3)[410/(12)^3 \text{ ft}^3](0.90)(3000/60 \text{ rev/sec})/2 = 0.3945 \text{ lbm/sec}$$

fuel flow rate into engine using Eq. (2-55)

$$\dot{m}_f = \dot{m}_a/(AF) = (0.3945 \text{ lbm/sec})/15.2 = 0.02595 \text{ lbm/sec} = 93.43 \text{ lbm/hr}$$

fuel lost in exhaust

$$(\dot{m}_f)_{\text{lost}} = (93.43 \text{ lbm/hr})(0.0172) = \underline{1.61 \text{ lbm/hr}}$$

(c)

$$\dot{Q}_{\text{lost}} = \dot{m}_f Q_{\text{Hv}} = (1.61 \text{ lbm/hr})(43,000 \text{ kJ/kg})/(2.326 \text{ [kJ/kg]/[BTU/lbm]})$$
$$= 29,764 \text{ BTU/hr} = (29,764 \text{ BTU/hr})/(2545 \text{ BTU/hr/hp}) = \underline{11.7 \text{ hp}}$$

(9-6)

$$\text{lead in gasoline} = (0.15 \text{ gm/L})(3.785 \text{ L/gal})/(1000/2.205 \text{ gm/lbm}) = 0.00125 \text{ lbm/gal}$$

$$\text{lead exhausted} = (1/16 \text{ gal/mile})(0.00125 \text{ lbm/gal})(0.45) = \underline{0.0000352 \text{ lbm/mile}}$$

$$= (0.0000352 \text{ lbm/mile})(55 \text{ miles/hr})(24 \text{ hr/day}) = \underline{0.046 \text{ lbm/day}}$$

(9-7)

(a)

use Eq. (2-71) for air flow rate into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0022)(0.92)(2500/60)/2 = 0.0498 \text{ kg/sec}$$

Eq. (2-55) gives flow rate of fuel

$$\dot{m}_f = \dot{m}_a / (AF) = (0.0498 \text{ kg/sec})/21 = 0.00237 \text{ kg/sec}$$

for 1 kgmole of $C_{12.3}H_{22.2}$ fuel

$$\text{mass of carbon} = (12.3)(12) = 147.6 \text{ kg}$$

$$\text{mass of hydrogen} = (22.2)(1) = 22.2 \text{ kg}$$

$$\% \text{ of carbon by mass} = (147.6/169.8)(100) = 86.93\%$$

mass flow rate of soot

$$\dot{m}_{\text{soot}} = (0.00237 \text{ kg/sec})(0.8693)(0.004)(1.2)(1.25)(3600 \text{ sec/hr}) = \underline{0.0445 \text{ kg/hr}}$$

(b)

$$\dot{Q}_{\text{lost}} = \dot{m}_{\text{soot}} Q_{\text{HV}} = (0.0445/3600 \text{ kg/sec})(33,800 \text{ kJ/kg}) = \underline{0.42 \text{ kW}}$$

(c)

volume of soot exhausted

$$\dot{V}_{\text{soot}} = \dot{m}/\rho = (0.0445 \text{ kg/hr})/(1400 \text{ kg/m}^3) = 0.0000318 \text{ m}^3/\text{hr}$$

volume of 1 particle

$$V_{\text{part}} = (\pi/6)d^3 = (\pi/6)(20 \times 10^{-9} \text{ m})^3 = 4.19 \times 10^{-24} \text{ m}^3/\text{part}$$

volume of 1 cluster

$$V_{\text{cluster}} = (2000)(4.19 \times 10^{-24} \text{ m}^3) = 8.38 \times 10^{-21} \text{ m}^3/\text{cluster}$$

number of clusters

$$(0.0000318 \text{ m}^3/\text{hr})/(8.38 \times 10^{-21} \text{ m}^3/\text{cluster}) = \underline{3.79 \times 10^{15} \text{ clusters/hr}}$$

(9-8)

(a)

use Eq. (2-65) for indicated power

$$\dot{W}_i = \dot{Q}_{in} \eta_i = \dot{m}_f Q_{HV} \eta_c \eta_i = (0.00237 \text{ kg/sec})(42,500 \text{ kJ/kg})(0.98)(0.61) = 60.2 \text{ kW}$$

use Eq. (2-62) for brake power

$$\dot{W}_b = \dot{W}_i \eta_m = (60.2 \text{ kW})(0.71) = 42.8 \text{ kW}$$

Eq. (2-60)

$$\text{bsfc} = \dot{m}_f / \dot{W}_b = (0.00237 \text{ kg/sec})(3600 \text{ sec/hr})(1000 \text{ gm/kg}) / (42.8 \text{ kW}) = \underline{199 \text{ gm/kW-hr}}$$

(b)

Eq. (2-73)

$$(\text{SE})_{\text{soot}} = \dot{m}_{\text{soot}} / \dot{W}_b = (0.0445 \text{ kg/hr})(1000 \text{ gm/kg}) / (42.8 \text{ kW}) = \underline{1.04 \text{ gm/kW-hr}}$$

(c)

Eq. (2-74) $(\text{EI})_{\text{soot}} = \dot{m}_{\text{soot}} / \dot{m}_f$

$$= [(0.0445 \text{ kg/hr})(1000 \text{ gm/kg})] / [(0.00237 \text{ kg/sec})(3600 \text{ sec/hr})] = \underline{5.2 \text{ gm}_{\text{soot}}/\text{kg}_{\text{fuel}}}$$

(9-9)

(a)

volume of boundary-layer in one cylinder

$$V_{BL} = \pi (6 \text{ cm}) (2 \text{ cm}) (0.01 \text{ cm}) + (\pi/4) (6 \text{ cm})^2 (0.01 \text{ cm}) (2 \text{ sides}) = 0.942 \text{ cm}^3$$

volume of clearance volume

$$V_{\text{clear}} = (\pi/4) (6 \text{ cm})^2 (2 \text{ cm}) = 56.55 \text{ cm}^3$$

percent of total volume in boundary-layer (which=% of fuel)

$$\% = [(0.942) / (56.55)] (100) = \underline{1.67 \%}$$

(b)

$$\begin{aligned} Q_{\text{lost}} &= m_f Q_{HV} = [(0.040 \text{ kg/sec})(0.0167)] (43,000 \text{ kJ/kg}) \\ &= \underline{28.7 \text{ kJ/sec} = 28.7 \text{ kW}} \end{aligned}$$

(c)

$$(\text{EI})_{\text{HC}} = m_{\text{HC}} / m_f = [(0.0167) m_f] / (m_f) = 0.0167 \text{ kg}_{\text{HC}} / \text{kg}_f = \underline{16.7 \text{ gm}_{\text{HC}} / \text{kg}_f}$$

(9-10)

(a)

for 1 cylinder $V_d = (6.4 \text{ L})/8 = 0.8 \text{ L} = 0.0008 \text{ m}^3$

Eq. (2-12) for clearance volume of 1 cylinder

$$r_c = 10.4 = (V_d + V_c)/V_c = (0.0008 + V_c)/V_c \quad V_c = 0.0000851 \text{ m}^3$$

clearance volume of 8 cylinders $V_c = (0.0000851 \text{ m}^3)(8) = 0.000681 \text{ m}^3 = 681 \text{ cm}^3$

crevice volume $V_{\text{crevice}} = (681 \text{ cm}^3)(0.028) = \underline{19.1 \text{ cm}^3}$

(b)

using Fig. 3-2 and Eqs. (3-4) and (3-5)

$$T_2 = T_1(r_c)^{k-1} = (338 \text{ K})(10.4)^{0.35} = 767 \text{ K}$$

$$P_2 = P_1(r_c)^k = (120 \text{ kPa})(10.4)^{1.35} = 2833 \text{ kPa}$$

mass in crevice

$$m_{\text{crev}} = PV/RT = (2833 \text{ kPa})(0.0000191 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(458 \text{ K}) = 0.000412 \text{ kg}$$

mass in clearance volume

$$m_{\text{clear}} = (2833 \text{ kPa})(0.000681 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(767 \text{ K}) = 0.008764 \text{ kg}$$

$$\% \text{ of mass in crevice volume} = [(0.000412)/(0.008764 + 0.000412)](100) = \underline{4.5\%}$$

(9-11)

(a)

Eq. (2-71) for air flow rate into engine

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0064)(0.89)(5500/60)/2 = 0.3083 \text{ kg/sec}$$

Eq. (2-55) for fuel flow rate

$$\dot{m}_f = \dot{m}_a / (\text{AF}) = (0.3083 \text{ kg/sec})/14.2 = 0.0217 \text{ kg/sec}$$

mass of fuel in exhaust

$$(\dot{m}_f)_{\text{ex}} = [(0.0217)(3600) \text{ kg/hr}](0.045 \text{ trapped})(0.40 \text{ not burned}) = \underline{1.406 \text{ kg/hr}}$$

(b)

$$\dot{Q}_{\text{lost}} = \dot{m}_f Q_{\text{HV}} = (1.406 \text{ kg/hr})(44,300 \text{ kJ/kg})/(3600 \text{ sec/hr}) = \underline{17.3 \text{ kW}}$$

(9-12)

(a) use time rate form of Eq. (5-22) for flow of air-fuel mixture
 $\dot{m}_a = \lambda_a V_a \rho_a N/n = (0.95)(0.196 \text{ m}^3/\text{cycle})(1.181 \text{ kg/m}^3)(220/60 \text{ rev/sec})/(1 \text{ rev/cycle})$
 $= 0.806 \text{ kg/sec}$

air flow in with AF = 22

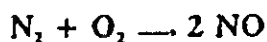
$$\dot{m}_a = (0.806 \text{ kg/sec})(22/23) = 0.7710 \text{ kg/sec} = 2776 \text{ kg/hr} = 95.72 \text{ kgmoles/hr}$$

with air having 3.76 moles of N_2 for every 1 mole of O_2

moles of N_2 in per hour

$$(95.72 \text{ kgmoles/hr})(3.76/4.76) = 75.61 \text{ kgmoles/hr}$$

for every mole of N_2 converted there will be 2 moles of NO



NO generated

$$(75.61 \text{ kgmoles/hr})(2)(0.001 \text{ converted}) = 0.1512 \text{ kgmoles/hr}$$

$$\dot{m}_{NO} = (0.1512 \text{ kgmoles/hr})(30 \text{ kg/kgmole}) = \underline{4.54 \text{ kg/hr}}$$

(b)

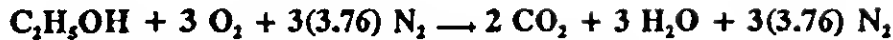
from Eq. (9-29) 1 mole of NH_3 is needed for every mole of NO

$$\dot{m}_{NH_3} = (0.1512 \text{ kgmoles/hr})(17 \text{ kg/kgmole}) = \underline{2.57 \text{ kg/hr}}$$

(9-13)

(a)

stoichiometric combustion equation



to find temperature use Eqs. (4-8) and (4-5)

(using enthalpy values from Introduction to Thermodynamics,
by Sonntag and Van Wylen, 3rd ed., John Wiley and Sons, 1991)

$$\sum_{\text{PROD}} N_i (h_i^\circ + \Delta h)_i = \sum_{\text{REACT}} N_i (h_i^\circ + \Delta h)_i$$

$$2[(-393,522) + \Delta h_{\text{CO}_2}] + 3[(-241,826) + \Delta h_{\text{H}_2\text{O}}] + 3(3.76)[(0) + \Delta h_{\text{N}_2}] \\ \longrightarrow [-199,000] + 3[(0) + (12,499)] + 3(3.76)[(0) + (11,937)]$$

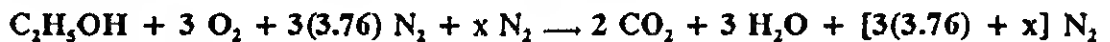
$$2 \Delta h_{\text{CO}_2} + 3 \Delta h_{\text{H}_2\text{O}} + 11.28 \Delta h_{\text{N}_2} = 1,485,668$$

find temperature to satisfy this by trial and error

$$\underline{T_{\text{max}} = 2652 \text{ K}}$$

(b)

add x amount of EGR (N_2) to lower T_{max} to 2400 K



Eq. (4-8) at $T = 2400 \text{ K}$

$$2[(-393,522) + (115,779)] + 3[(-241,826) + (93,741)] + (11.28 + x)[(0) + (70,640)] \\ = [-199,000] + 3[(0) + (12,499)] + 3(3.76)[(0) + (11,937)] + x[(0) + (21,463)]$$

$$x = 3.580 \text{ kgmoles for 1 kgmole of fuel burned} \\ = (3.580 \text{ kgmoles})(28 \text{ kg/kgmole}) = 100.2 \text{ kg}$$

mass of air in for 1 kgmole of fuel

$$(3)(4.76)(29) = 414.1 \text{ kg}$$

mass of fuel in for 1 kgmole of fuel

$$(1)(46) = 46.0 \text{ kg}$$

total mass in for each mole of fuel

$$m_{\text{in}} = 100.2 + 414.1 + 46.0 = 560.3 \text{ kg}$$

Eq. (9-31) for 1 kgmole of fuel

$$\text{EGR} = [\dot{m}_{\text{EGR}}/\dot{m}_i](100) = [(100.2)/(560.3)](100) = \underline{17.9\%}$$

(9-14)

from Sec. 9-8 volume of catalytic converter

$$V_{\alpha} \approx \frac{1}{2} V_d = 1.4 \text{ L} = 0.0014 \text{ m}^3$$

(a) heat needed

$$Q = mc_p \Delta T = \rho V_{\alpha} c_p \Delta T \\ = (3970 \text{ kg/m}^3) (0.0014 \text{ m}^3) (20\%) (0.765 \text{ kJ/kg-K}) (125^\circ) = \underline{106.2 \text{ kJ}}$$

(b) Power = (24 volts)(600 amps) = 14,400 W = 14.40 kW = 14.40 kJ/sec

$$\text{time } t = (106.2 \text{ kJ}) / (14.40 \text{ kJ/sec}) = \underline{7.4 \text{ sec}}$$

(9-15)

(a) use a time rate form of Eq. (5-22) to get rate of air-fuel mixture ingested

$$\dot{m}_{\text{ing}} = \lambda_{\alpha} V_d \rho_a N/n = (0.88) (0.00002 \text{ m}^3/\text{cycle}) (1.181 \text{ kg/m}^3) (900/60 \text{ rev/sec}) / (1 \text{ rev/cycle}) \\ = 0.000312 \text{ kg/sec} = 1.122 \text{ kg/hr}$$

use a time rate form of Eq. (5-23) to get rate of air-fuel mixture trapped

$$\dot{m}_{\text{trap}} = \lambda_{\alpha} V_d \rho_a N/n = (0.72) (0.00002 \text{ m}^3/\text{cycle}) (1.181 \text{ kg/m}^3) (900/60 \text{ rev/sec}) / (1 \text{ rev/cycle}) \\ = 0.000255 \text{ kg/sec} = 0.918 \text{ kg/hr}$$

mass flow of air-fuel in exhaust due to valve

overlap = mass flow ingested - mass flow trapped

$$(\dot{m}_{\text{ex}})_{\text{overlap}} = (1.122 \text{ kg/hr}) - (0.918 \text{ kg/hr}) = 0.204 \text{ kg/hr}$$

use Eq. (2-57) for actual air-fuel ratio

$$(AF)_{\text{act}} = (AF)_{\text{stoich}} / \phi = 14.6/1.08 = 13.52$$

mass rate of fuel and oil in exhaust

$$(\dot{m}_{\text{HC}})_{\text{ex}} = (0.204 \text{ kg/hr}) / 13.52 = \underline{0.0140 \text{ kg/hr}}$$

(b) mass rate of fuel and oil (HC) trapped in combustion chamber

$$(\dot{m}_{\text{HC}})_{\text{trap}} = (0.918 \text{ kg/hr}) / 13.52 = 0.0632 \text{ kg/hr}$$

$$\text{of this } \dot{m}_{\text{fuel}} = (0.0632 \text{ kg/hr}) (60/61) = 0.0622 \text{ kg/hr}$$

$$\dot{m}_{\text{oil}} = (0.0632 \text{ kg/hr}) (1/61) = 0.0010 \text{ kg/hr}$$

94% of fuel gets burned, so 6% does not get burned

$$(\dot{m}_{\text{fuel}})_{\text{n.b.}} = (0.0622 \text{ kg/hr}) (0.06) = 0.0037 \text{ kg/hr}$$

$$(\dot{m}_{\text{oil}})_{\text{n.b.}} = (0.0010 \text{ kg/hr}) (0.28) = 0.0003 \text{ kg/hr}$$

$$\text{total rate of HC not burned } \dot{m}_{\text{HC}} = 0.0037 + 0.0003 = \underline{0.0040 \text{ kg/hr}}$$

$$(c) (\dot{m}_{\text{HC}})_{\text{total}} = (0.014 \text{ kg/hr}) + (0.0040 \text{ kg/hr}) = \underline{0.018 \text{ kg/hr}}$$

(9-16)

(a)

air flow into engine using Eq. (2-71)

$$\begin{aligned}\dot{m}_r &= \eta_v \rho_a V_d N / n \\ &= (.93) (1.181 \text{ kg/m}^3) (.0032 \text{ m}^3/\text{cycle}) / (3600/60 \text{ rev/sec}) / (2 \text{ rev/cycle}) \\ &= 0.1054 \text{ kg/sec} = 379.58 \text{ kg/hr}\end{aligned}$$

Eq. (2-55) for fuel flow

$$\dot{m}_f = \dot{m}_r (AF) = (379.58 \text{ kg/hr}) / (22) = \underline{17.25 \text{ kg/hr}}$$

(b)

$$\begin{aligned}\dot{m}_{\text{sulfur}} &= (17.25 \text{ kg/hr}) [(450) / (1,000,000)] = 0.00776 \text{ kg/hr} \\ &= \underline{7.76 \text{ gm/hr}}\end{aligned}$$

(c)

Eq. (2-73)

$$(SE)_{\text{sulfur}} = \dot{m}_{\text{sulfur}} / \dot{W}_b = (7.76 \text{ kg/hr}) / (92 \text{ kW}) = \underline{0.0844 \text{ gm/kW-hr}}$$

(d)

flow rate of sulfur into environment

$$\dot{m}_{\text{sulfur}} = (7.76 \text{ gm/hr}) = (.00776 \text{ kg/hr}) / (32 \text{ kg/kgmole}) = .000243 \text{ kgmole/hr}$$

using Eqs. (9-15) and (9-18)

one mole of sulfur produces one mole of sulfurous acid

$$\begin{aligned}\dot{m}_{\text{acid}} &= (.000243 \text{ kgmole/hr}) (82 \text{ kg/kgmole}) (24 \text{ hr/day}) \\ &= \underline{0.477 \text{ kg/day}}\end{aligned}$$

(9-17)

use Eq. (2-71) for flow rate of air into engine

$$\dot{m}_r = \rho_a V_d \eta_v N / n = (1.181) (0.0052) (0.96) (2800/60) / 2 = 0.1376 \text{ kg/sec}$$

Eq. (2-55) for fuel flow rate

$$\dot{m}_f = \dot{m}_r (AF) = (0.1376 \text{ kg/sec}) / 20 = 0.00688 \text{ kg/sec}$$

(a)

flow of sulfur through engine

$$\begin{aligned}\dot{m}_{\text{sulfur}} &= (0.00688 \text{ kg/sec}) (500 / 1,000,000) = 3.44 \times 10^{-6} \text{ kg/sec} \\ &= (3.44 \times 10^{-6} \text{ kg/sec}) (3600 \text{ sec/hr}) (1000 \text{ gm/kg}) = \underline{12.4 \text{ gm/hr}} \\ &= (0.0124 \text{ kg/hr}) / (32 \text{ kg/kgmole}) = 0.000388 \text{ kgmoles/hr}\end{aligned}$$

(b)

from Eq. (9-15)

for 1 mole of S there is 1 mole of SO_2 formed

from Eq. (9-18) for 1 mole of SO_2 there is 1 mole of H_2SO_3 formed

mass flow of sulfurous acid to environment

$$\dot{m}_{\text{H}_2\text{SO}_3} = (0.000388 \text{ kgmoles/hr}) (82 \text{ kg/kgmole}) = \underline{0.032 \text{ kg/hr}}$$

(9-18)

(a)

rate of fuel used

$$\dot{m}_f = (8 \text{ kg/km})(100 \text{ km/hr}) = 8 \text{ kg/hr}$$

flow rate of CO

$$\dot{m}_{\text{co}} = (12 \text{ gm/kg})(8 \text{ kg/hr}) = 96 \text{ gm/hr}$$

Eq. (2-73)

$$(\text{SE})_{\text{co}} = \dot{m}_{\text{co}} / \dot{W}_b = (96 \text{ gm/hr}) / (40 \text{ kW}) = \underline{2.40 \text{ gm/kW-hr}}$$

(b)

$$\begin{aligned} [(\text{SE})_{\text{co}}]_{\text{ave}} &= (2.40 \text{ gm/kW-hr}) \underset{\text{hot}}{(1 - .95) (90\% \text{ of time})} + (2.40) \underset{\text{cold}}{(10\% \text{ of time})} \\ &= \underline{0.348 \text{ gm/kW-hr}} \end{aligned}$$

(c)

$$\% = [(0.240) / (0.348)] (100) = \underline{69.0\%}$$

(9-19)

More exhaust smoke would be expected. Fuel with the lower cetane number will not self-ignite as readily and there will be a longer ignition delay between start of injection and start of combustion. More fuel will be injected before ignition occurs and the overall air-fuel ratio will be more fuel-rich when combustion starts. Solid carbon (smoke) is generated in the fuel-rich part of the combustion chamber where there is not enough oxygen to form CO_2 . This fuel-rich zone would be larger under these conditions.

(9-20)

(a)

yearly consumption of gasoline by 1 automobile

$$(16,000 \text{ km/year})[(15 \text{ L})/(100 \text{ km})] = 2400 \text{ L/year}$$

lead into atmosphere by average automobile

$$\dot{m}_L = (2400 \text{ L/year})((0.15 \text{ gm/L})(0.35 \text{ exhausted})) = 126 \text{ gm/yr} = \underline{0.126 \text{ kg/yr}}$$

(b)

$$\begin{aligned} (2.33 \times 10^9 \text{ bbl/yr})(160 \text{ L/bbl})(0.15 \text{ gm/L})(0.35 \text{ exhausted}) &= 1.96 \times 10^{10} \text{ gm/yr} \\ &= \underline{1.96 \times 10^7 \text{ kg/yr}} \end{aligned}$$

(9-21) exhaust flow rate

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_a = \dot{m}_f(1 + AF) = (5 \text{ lbm/hr})(1 + 14.6) = 78 \text{ lbm/hr}$$

flow rate of CO

$$\begin{aligned}\dot{m}_{CO} &= (0.006)(78 \text{ lbm/hr}) = 0.468 \text{ lbm/hr} \\ &= (0.468 \text{ lbm/hr})/(28 \text{ lbm/lbmole}) = 0.0167 \text{ lbmole/hr}\end{aligned}$$

moles of air in garage

$$\begin{aligned}N_{air} &= PV/RT = [(14.7)(144) \text{ lbf/ft}^2][(20)(20)(8) \text{ ft}^3]/(1545 \text{ ft}\cdot\text{lbf/lbmole}\cdot^\circ\text{R})(500^\circ \text{ R}) \\ &= 8.769 \text{ lbmmoles}\end{aligned}$$

to become dangerous

$$\text{CO} = 10 \text{ ppm of air} = (10 \times 10^{-6})(8.769 \text{ lbmmoles}) = 8.769 \times 10^{-5} \text{ lbmmoles}$$

$$\begin{aligned}\text{time } t &= (8.769 \times 10^{-5} \text{ lbmmoles})/(0.0167 \text{ lbmmoles/hr}) \\ &= 0.00525 \text{ hr} = \underline{0.315 \text{ min}} = 19 \text{ sec}\end{aligned}$$

(9-22)

(a) mass flow rate of HC

$$\dot{m}_{HC} = (1.4 \text{ gm/km})(100 \text{ km/hr}) = 140 \text{ gm/hr}$$

$$\text{Eq. (2-73)} \quad (SE)_{HC} = \dot{m}_{HC}/\dot{W}_b = (140 \text{ gm/hr})/(32 \text{ kW}) = \underline{4.4 \text{ gm/kW}\cdot\text{hr}}$$

(b) mass flow rate of CO upstream of converter

$$\dot{m}_{CO} = (12 \text{ gm/km})(100 \text{ km/hr}) = 1200 \text{ gm/hr}$$

mass flow rate of CO downstream of converter

$$\dot{m}_{CO} = (1200 \text{ gm/hr})(0.05 \text{ not removed}) = 60 \text{ gm/hr}$$

$$(SE)_{CO} = (60 \text{ gm/hr})/(32 \text{ kW}) = \underline{1.88 \text{ gm/kW}\cdot\text{hr}}$$

(c) exhaust flow out = mass flow in

$$\begin{aligned}\dot{m}_{ex} &= \dot{m}_{in} = \dot{m}_a + \dot{m}_f = \dot{m}_f(AF + 1) \\ &= [(6 \text{ kg/100 km})(100 \text{ km/hr})](14.6 + 1) = 93.6 \text{ kg/hr} = 93,600 \text{ gm/hr}\end{aligned}$$

mass flow rate of NOx upstream of converter

$$\dot{m}_{NOx} = (1.1 \text{ gm/km})(100 \text{ km/hr}) = 110 \text{ gm/hr}$$

mole fraction of NOx using Eq. (4-1)

$$x_{NOx} = N_{NOx}/N_{total} = (\dot{m}_{NOx}/M_{NOx})/(\dot{m}_{total}/M_{air}) = (110/46)/(93,600/29) = 0.00074 = \underline{740 \text{ ppm}}$$

$$(d) \quad (1.4)(1 - 0.95)(0.9) + (1.4)(0.1) = \underline{0.203 \text{ gm/km}}$$

$$(e) \quad \% = [(1.4)(0.1)]/0.203 = 0.690 = \underline{69.0\%}$$

CHAPTER 10

(10-1)

(a) for 1 cylinder $V_d = (6.6 \text{ L})/6 = 1.1 \text{ L} = 0.0011 \text{ m}^3$

Eq. (2-71)

$$\dot{m}_s = \rho V_d \eta_r N/n = (1.181)(0.0011)(0.89)(3000/60)/2 = 0.0289 \text{ kg/sec}$$

$$\text{Vel} = \dot{m}_s / \rho A = (0.0289 \text{ kg/sec}) / (1.181 \text{ kg/m}^3) [(\pi/4)(0.04 \text{ m})^2] = 19.47 \text{ m/sec}$$

(b) Reynolds number using property values from Ref. [63]

$$\text{Re} = (\text{Vel})d\rho/\mu = (19.47 \text{ kg/sec})(0.04 \text{ m})(1.181 \text{ kg/m}^3)/(1.846 \times 10^{-5} \text{ kg/m-sec}) \\ = 49,825 \text{ turbulent flow}$$

(c) Nusselt number using Dittus-Boelter equation and property values from Ref. [63]

$$\text{Nu} = 0.023 \text{ Re}^{0.8} \text{ Pr}^{0.4} = (0.023)(49,825)^{0.8} (0.708)^{0.4} = 114.7 = hd/k$$

where: Pr = Prandtl number

h = convection heat transfer coefficient

d = inside diameter of runner

k = thermal conductivity

c_p = specific heat

A = inside surface area of runner #1

ΔT = temperature difference between air and wall

$$\text{let } \Delta T = T_{\text{wall}} - (T_s)_{\text{in}} = 67^\circ \text{ C} - 27^\circ \text{ C} = 40^\circ$$

$$h = (\text{Nu})k/d = (114.7)(0.02624 \text{ W/m-K})/(0.04 \text{ m}) = 75.2 \text{ W/m}^2\text{-K}$$

$$\dot{Q} = hA\Delta T = \dot{m}c_p(T_{\text{out}} - T_{\text{in}}) = (75.2 \text{ W/m}^2\text{-K})[\pi(0.04 \text{ m})(0.4 \text{ m})](40^\circ) \\ = (0.0289 \text{ kg/sec})(1005 \text{ J/kg-K})(T_{\text{out}} - 27^\circ \text{ C})$$

temperature out of runner = temperature entering cyl #1

$$T_{\text{out}} = T_{\text{enter}} = 32.2^\circ \text{ C}$$

(d) in runner #3, \dot{m} , Re, Pr, Nu, and h are all the same as in runner #1

$$\dot{Q} = (75.2 \text{ W/m}^2\text{-K})[\pi(0.04 \text{ m})(0.15 \text{ m})]\Delta T = (0.0289 \text{ kg/sec})(1005 \text{ J/kg-K})(5.2^\circ) \\ \Delta T = 107^\circ \text{ C}$$

$$T_{\text{wall}} = T_{\text{in}} + \Delta T = 27^\circ + 107^\circ = 134^\circ \text{ C}$$

(10-2)

(a)

use Eq. (2-55) for fuel flow rate

$$\dot{m}_f = \dot{m}_a / (AF) = (0.0289 \text{ kg/sec}) / 14.6 = 0.00198 \text{ kg/sec}$$

$$\dot{Q}_{\text{evap}} = \dot{m}_f h_{fg} (\% \text{ evaporated}) = (0.00198 \text{ kg/sec})(307 \text{ kJ/kg})(0.40) = 0.2431 \text{ kJ/sec}$$

this cools the air-fuel mixture (use low temp value of c_p)

$$\dot{Q}_{\text{evap}} = \dot{m}_m c_p \Delta T = (0.0289 + 0.00198) \text{ kg/sec} (1.005 \text{ kJ/kg-K}) \Delta T$$

$$\Delta T = 7.8^\circ \text{ C}$$

$$T_{\text{entering}} = 32.2^\circ - \Delta T = 32.2^\circ - 7.8^\circ = \underline{24.4^\circ \text{ C}}$$

(b)

$$\dot{m}_f = (0.0289 \text{ kg/sec}) / 9 = 0.00321 \text{ kg/sec}$$

$$\begin{aligned} \dot{Q}_{\text{evap}} &= (0.00321 \text{ kg/sec})(873 \text{ kJ/kg})(0.40) = 1.121 \text{ kJ/sec} \\ &= (0.0289 + 0.00321) \text{ kg/sec} (1.005 \text{ kJ/kg-K}) \Delta T \end{aligned}$$

$$\Delta T = 34.7^\circ \text{ C}$$

$$T_{\text{entering}} = 32.2^\circ - 34.7^\circ = \underline{-2.5^\circ \text{ C}}$$

(10-3)

Eq. (2-8) for 1 cylinder

$$V_d = 0.0011 \text{ m}^3 = (\pi/4) B^2 S = (\pi/4) B^2 (0.9 \text{ B})$$

$$B = 0.1159 \text{ m} = 11.59 \text{ cm}$$

Eq. (2-15) gives area of piston face

$$A_p = (\pi/4) B^2 = (\pi/4) (0.1159 \text{ m})^2 = 0.01055 \text{ m}^2$$

Eq. (10-7) using viscosity value from Ref. [63]

$$\begin{aligned} \text{Re} &= [(\dot{m}_a + \dot{m}_f) B] / (A_p \mu_f) \\ &= [(0.0289 + 0.00321) (0.1159)] / [(0.01055) (1.846 \times 10^{-5})] = \underline{19,109} \end{aligned}$$

(10-4)

assume $\Delta T = (T_{in} - T_{out}) = 100^\circ \text{C}$

average bulk temperature

$$T_{bulk} = (477^\circ + 377^\circ)/2 = 427^\circ \text{C} = 700 \text{ K}$$

air property values from Ref. [63] at average bulk temperature:

density	$\rho = 0.5030 \text{ kg/m}^3$
kinematic viscosity	$\nu = 66.25 \times 10^{-6} \text{ m}^2/\text{sec}$
thermal conductivity	$k = 0.05230 \text{ W/m-K}$
specific heat	$c_p = 1075.2 \text{ J/kg-K}$
Prandtl number	$Pr = 0.684$

mass flow rate of exhaust for entire engine

$$\dot{m}_{ex} = \dot{m}_a + \dot{m}_f = 0.0289 + 0.00321 = (0.03211 \text{ kg/sec})(6 \text{ cyl}) = 0.19266 \text{ kg/sec}$$

$$Vel = \dot{m}_{ex}/\rho A = (0.19266 \text{ kg/sec})/(0.5030 \text{ kg/m}^3)[(\pi/4)(0.065 \text{ m})^2] = 115.4 \text{ m/sec}$$

Reynolds number

$$Re = (Vel)d/\nu = (115.4 \text{ m/sec})(0.065 \text{ m})/(66.25 \times 10^{-6}) = 113,223$$

Nusselt number using Dittus-Boelter equation from Ref. [63]

$$Nu = 0.023 Re^{0.8} Pr^{0.3} = (0.023)(113,223)^{0.8}(0.684)^{0.3} = 226.6$$

this is increased by a factor of 2 due to pulsed flow of exhaust

$$Nu = (226.6)(2) = 453.2 = hd/k$$

convection heat transfer coefficient

$$h = (Nu)k/d = (453.2)(0.05230 \text{ W/m-K})/(0.065 \text{ m}) = 364.7 \text{ W/m}^2\text{-K}$$

convection heat transfer

$$\begin{aligned} \dot{Q} &= h(\text{surface area})(T_{bulk} - T_{wall}) \\ &= (364.7 \text{ W/m}^2\text{-K})[\pi(0.065 \text{ m})(1.5 \text{ m})](700 - 500)\text{K} = 22,342 \text{ W} = \dot{m}_{ex}c_p\Delta T \\ &= (0.19266 \text{ kg/sec})(1075.2 \text{ J/kg-K})\Delta T \end{aligned}$$

$$\Delta T = 108^\circ$$

temperature of exhaust entering catalytic converter

$$T_{ex} = 477^\circ\text{C} - \Delta T = 477^\circ\text{C} - 108^\circ = 369^\circ\text{C} = 642\text{K}$$

2nd iteration using $\Delta T = 108^\circ\text{C}$ to get better bulk temperature:

average bulk temperature	$T_{\text{bulk}} = 696 \text{ K}$
density	$\rho = 0.5056 \text{ kg/m}^3$
kinematic viscosity	$\nu = 65.63 \times 10^{-6} \text{ m}^2/\text{sec}$
thermal conductivity	$k = 0.05199 \text{ W/m-K}$
specific heat	$c_p = 1074.3 \text{ J/kg-K}$
Prandtl number	$Pr = 0.684$
velocity	$Ve1 = 114.8 \text{ m/sec}$
Reynolds number	$Re = 113,698$
Nusselt number	$Nu = 454.8$
convection heat transfer coefficient	$h = 363.8 \text{ W/m}^2\text{-K}$
heat transfer	$\dot{Q} = 21,841 \text{ W}$
change in temperature	$\Delta T = 106^\circ\text{C}$
exhaust temperature entering catalytic converter	$T_{ex} = 371^\circ\text{C} = 644 \text{ K}$

these values are close enough so a 3rd iteration is not needed

(10-5)

(a)

using Fig. 10-1 at 2000 RPM

$$\dot{Q}_{ex} \approx \dot{W}_b = \underline{20 \text{ kW}}$$

(b)

$$\dot{Q}_{\text{friction}} \approx \frac{1}{4} \dot{W}_b = \frac{1}{4}(20 \text{ kW}) = \underline{5 \text{ kW}}$$

(c)

$$\dot{Q}_{\text{coolant}} \approx 1.3 \dot{W}_b = 1.3(20 \text{ kW}) = \underline{26 \text{ kW}}$$

(10-6)

(a) using Fig. 10-1 at 2500 RPM $\dot{Q}_{\text{coolant}} \approx 1.11 \dot{W}_b = 1.11(30\text{hp}) = 33.3\text{hp}$

mass flow rate of coolant flow

$$\dot{m}_c = (25 \text{ gal/min})(60 \text{ min/hr})(62.4 \text{ lbm/ft}^3)/(7.481 \text{ gal/ft}^3) = 12,512 \text{ lbm/hr}$$

$$\dot{Q}_{\text{coolant}} = \dot{m}_c c_p \Delta T = (33.3 \text{ hp})(2545 \text{ BTU/hr/hp}) = (12,512 \text{ lbm/hr})(1 \text{ BTU/lbm}^\circ\text{R})\Delta T$$
$$\Delta T = 7^\circ \text{ F}$$

$$T_{\text{exit}} = T_{\text{in}} + \Delta T = 220^\circ + 7^\circ = \underline{227^\circ \text{ F}}$$

(b) velocity of air through radiator

$$\text{Vel} = [(30 \text{ miles/hr})(5280 \text{ ft/mile})/(3600 \text{ sec/hr})](1.1) = 48.4 \text{ ft/sec}$$

mass flow of air

$$\dot{m}_a = \rho(\text{Vel})A = (0.0739 \text{ lbm/ft}^3)(48.4 \text{ ft/sec})(4.5 \text{ ft}^2) = 16.1 \text{ lbm/sec}$$

33.3 hp must be dissipated

$$\dot{Q}_{\text{radiator}} = \dot{m}_a c_p \Delta T$$
$$(33.3 \text{ hp})(2545/3600 \text{ BTU/sec/hp}) = (16.1 \text{ lbm/sec})(0.240 \text{ BTU/lbm}^\circ\text{R})\Delta T$$
$$\Delta T = 6^\circ \text{ F}$$

$$T_{\text{exit}} = T_{\text{in}} + \Delta T = 75^\circ + 6^\circ = \underline{81^\circ \text{ F}}$$

(10-7)

approximate ratio of cylinder volumes

$$R_{\text{vol}} = 320/290 = 1.103$$

approximate ratio of linear dimensions

$$R_{\text{lin}} = (1.103)^{1/3} = 1.033$$

approximate ratio of area dimensions

$$R_{\text{area}} = (1.033)^2 = 1.068$$

- (a) \dot{Q}_{in} will be proportional to cylinder volume for each engine
heat losses will be proportional to cylinder surface area
 $(\eta_i)_{320}/(\eta_i)_{290} \approx R_{\text{vol}}/R_{\text{area}} = 1.103/1.068 = 1.033$

3.3% greater indicated thermal efficiency in larger engine

- (b) if all temperatures are the same, heat transfer to coolant will be proportional to surface area

$$\dot{Q}_{320} \approx 1.068 \dot{Q}_{290}$$

6.8% greater heat flow to coolant in larger engine

(10-8)

Table 10-1 using propylene glycol-water table at -30°C gives a specific gravity of 1.038
using ethylene glycol-water table for a solution with a specific gravity of 1.038 gives:
 $T_{\text{freezing pt}} = -13.5^{\circ}\text{C}$

(10-9)

(a) $Q = mc_p\Delta T = (10\text{ kg})(900\text{ J/kg-K})(110 - 80)^{\circ}\text{C} = 270,000\text{ J}$
time $t = Q/\dot{Q}_{\text{loss}} = (270,000\text{ J})/(3\text{ J/sec}) = 90,000\text{ sec} = \underline{25\text{ hr}}$

(b) time $t = (80\text{ W-hr/kg})(10\text{ kg})/(3\text{ W}) = \underline{267\text{ hr}} = 11.1\text{ days}$

(c) to cool solid $Q = (350\text{ J/kg-K})(10\text{ kg})(80 - 10)^{\circ}\text{C} = 245,000\text{ J}$
time $t = Q/\dot{Q}_{\text{loss}} = (245,000\text{ J})/(3\text{ J/sec}) = 81,667\text{ sec} = 22.7\text{ hr}$

time to cool $t = 25 + 267 + 22.7 = \underline{314.7\text{ hr}} = 13.1\text{ days}$

(d) energy to change phase $Q = (80\text{ W-hr/kg})(10\text{ kg}) = 800\text{ W-hr}$

energy needed to heat coolant using $c_p = 4200\text{ J/kg-K}$ for coolant (water)
 $\dot{Q}' = \dot{m}c_p\Delta T = (0.09\text{ kg/sec})(4200\text{ J/kg-K})(80 - 20)^{\circ}\text{C} = 22,680\text{ W}$

time $t = Q/\dot{Q}' = (800\text{ W-hr})/(22,680\text{ W}) = 0.03527\text{ hr} = \underline{2.12\text{ min}} = 127\text{ sec}$

(10-10)

heat loss from 215°F to 175°F from Example Problem 10-5
 $Q_1 = 54.56\text{ BTU}$

heat loss during phase change
 $Q_2 = (6.2\text{ lbm})(0.60\text{ of total})(125\text{ BTU/lbm}) = 465\text{ BTU}$

total heat loss
 $Q = Q_1 + Q_2 = (54.56) + (465) = 519.56\text{ BTU}$

time of heat loss
 $t = (519.56\text{ BTU})/(11\text{ BTU/hr}) = \underline{47.23\text{ hr}} = 1\text{ day } 23\text{ hr } 14\text{ min}$

(10-11)

(a)

heat exchange in engine

$$Q = mc_p \Delta T$$

$$= (1000 \text{ BTU/min}) = [(20 \text{ gal/min})(8.41 \text{ lbm/gal})](1 \text{ BTU/lbm-}^\circ\text{R}) \Delta T$$

$$\Delta T = 6^\circ$$

$$T_{\text{exit}} = T_{\text{inlet}} + \Delta T = (200^\circ\text{F}) + (6^\circ) = \underline{206^\circ\text{F}}$$

(b)

mass flow rate of air

$$\dot{m}_a = \rho_a V A = (0.0739 \text{ lbm/ft}^3)(50 \text{ ft/sec})(4 \text{ ft}^2) = 14.78 \text{ lbm/sec}$$

for air

$$Q = mc_p \Delta T = (1000/60 \text{ BTU/sec}) = (14.78 \text{ lbm/sec})(0.240 \text{ BTU/lbm-}^\circ\text{R}) \Delta T$$

$$\Delta T = + \underline{4.7^\circ\text{F}}$$

(10-12)

$$(a) \text{ Eq. (2-9)} \quad V_d = N_c(\pi/4)B^2S = (12 \text{ cyl})(\pi/4)(0.142 \text{ m})^2(0.245 \text{ m}) = 0.0466 \text{ m}^3$$

air flow rate using Eq. (2-71)

$$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0466)(0.96)(980/60)/2 = 0.4315 \text{ kg/sec}$$

fuel flow rate using Eq. (2-55)

$$\dot{m}_f = \dot{m}_a / (AF) = (0.4315 \text{ kg/sec})/21 = 0.0205 \text{ kg/sec}$$

$$\text{exhaust flow rate} \quad \dot{m}_{\text{ex}} = \dot{m}_a + \dot{m}_f = 0.4315 + 0.0205 = 0.4520 \text{ kg/sec}$$

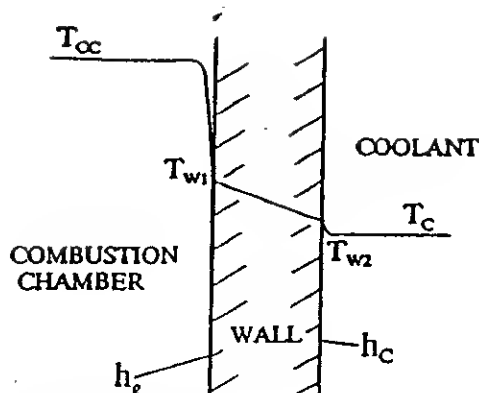
rate of exhaust enthalpy change in heat exchanger

$$\Delta \dot{H} = \dot{m}_{\text{ex}} c_p \Delta T = (0.4520 \text{ kg/sec})(1.108 \text{ kJ/kg-K})(577 - 227) \text{ K} = \underline{175.3 \text{ kW}}$$

(b)

$$\dot{m}_{\text{steam}} = \Delta \dot{H} / h_{fg} = [(175.3 \text{ kJ/sec})(0.98 \text{ efficiency})(3600 \text{ sec/hr})]/(2257 \text{ kJ/kg}) = \underline{274 \text{ kg/hr}}$$

(10-13)



$$(a) \quad \dot{q} = \dot{Q}/A = h_g \Delta T = 67,000 \text{ BTU/hr-ft}^2 = (22 \text{ BTU/hr-ft}^2\text{-}^\circ\text{R})(3800^\circ \text{R} - T_{w1})$$
$$T_{w1} = 755^\circ \text{R} = \underline{295^\circ \text{F}}$$

$$(b) \quad \dot{q} = \dot{Q}/A = k(\Delta T/\Delta x) = 67,000 \text{ BTU/hr-ft}^2 = (34 \text{ BTU/hr-ft-}^\circ\text{R})\Delta T/(0.4/12 \text{ ft})$$
$$\Delta T = 66^\circ \text{F} \quad T_{w2} = T_{w1} - \Delta T = 295^\circ - 66^\circ = \underline{229^\circ \text{F}}$$

$$(c) \quad \dot{q} = \dot{Q}/A = h_c(T_{w2} - T_c) = 67,000 \text{ BTU/hr-ft}^2 = h_c(229 - 185)^\circ\text{F}$$
$$h_c = \underline{1523 \text{ BTU/hr-ft}^2\text{-}^\circ\text{R}}$$

(10-14)

- (a) Engine A will have higher volumetric efficiency. Engine B will have higher steady state operating temperatures including cylinder wall temperature. This will heat the incoming air to a higher temperature which will reduce the air density, and thus reduce volumetric efficiency.

- (b) Engine B will have higher thermal efficiency because heat losses will be minimum due to the insulated walls.

Engine B will operate hotter than engine A so $(\dot{Q}_{in})_B$ will be at a higher temperature. By thermodynamic laws the higher the temperature at which energy is used (\dot{Q}_{in}) the higher will be the efficiency of that use.

Engine B would have to be a CI engine. Its walls would be too hot to operate as a SI engine, the air-fuel mixture would self-ignite during compression. CI engines operate at higher compression ratios and thus have higher thermal efficiency.

- (c) Engine B would have hotter exhaust. All temperatures in engine B would be higher. This reduces the thermal efficiency of engine B and contradicts some of part (b).
- (d) The higher temperatures of engine B would make it much more difficult to lubricate. There would be problems of thermal degradation of the lubricating oil.
- (e) Engine A would be a better SI engine. Engine B would operate too hot to be a SI engine, the air-fuel mixture would self-ignite during compression.

CHAPTER 11

(11-1)

(a)

$$\tan \phi = 3/9.10 = 0.3297 \quad \phi = 18.246^\circ$$

$$\text{Eq. (11-26)} \quad F_i = F_r \sin \phi = (1000 \text{ N}) \sin(18.246^\circ) = \underline{313 \text{ N}}$$

(b)

using Figs. 2-1 and 11-9

$$s = [a^2 + r^2]^{1/2} = [(3 \text{ cm})^2 + (9.10 \text{ cm})^2]^{1/2} = 9.5818 \text{ cm}$$

$$x = a + r - s = 3 + 9.10 - 9.5818 = \underline{2.52 \text{ cm}}$$

(c)

stroke and bore lengths

$$S = 2a = 2(3 \text{ cm}) = 6 \text{ cm}$$

$$B = S/0.94 = (6 \text{ cm})/0.94 = 6.38 \text{ cm}$$

$$\text{Eq. (2-9)} \quad V_d = N_c(\pi/4)B^2S = (4 \text{ cyl})(\pi/4)(6.38 \text{ cm})^2(6 \text{ cm}) = 767 \text{ cm}^3 = \underline{0.767 \text{ L}}$$

(d)

at TDC $\phi = 0^\circ$

$$\text{Eq. (11-26)} \quad F_i = F_r \sin \phi = F_r \sin(0^\circ) = \underline{0}$$

(11-2)

Cylinders get out-of-round because the side thrust force between the piston and cylinder wall is not uniform around the circumference of the cylinder. It is greatest (with the greatest wear) on the major thrust side, substantial on the minor thrust side, and less in other planes.

Wear is non-uniform along the length of the cylinder because of the changing force magnitude and the changing angle between the connecting rod and the centerline of the cylinder. This results in a changing side thrust force along the length of the cylinder, and a resulting non-uniform wear pattern.

Friction force on the piston should be zero at TDC and BDC because in theory the piston is stopped (no motion) at these points. In reality the piston assembly does not all stop at the same instance because of the very high acceleration rates at these points. Deflections in the connecting components and stretching or compression of the piston occur due to high mass inertia.

(11-3)

(a)

using Fig. 11-9

crank offset $a = S/2$

$$= (5.78 \text{ cm})/2 = 2.89 \text{ cm}$$

$$\sin \phi = 2.89/11.56 = 0.250$$

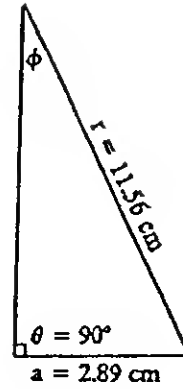
$$\phi = 14.478^\circ$$

Eq. (11-25)

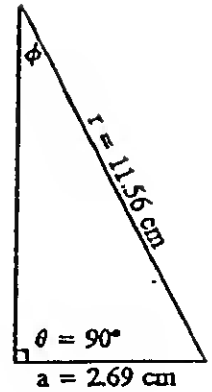
$$m(dU_p/dt) = 0 = -F_r \cos \phi + P(\pi/4)B^2 - F_t$$

$$= -F_r \cos(14.478^\circ) + (4500 \text{ kN/m}^2)(\pi/4)(0.06 \text{ m})^2 - 0.85 \text{ kN}$$

$$F_r = 12.27 \text{ kN compressive}$$



(a)



(c)

(b)

Eq. (11-27)

$$F_t = [-m(dU_p/dt) + P(\pi/4)B^2 - F_r] \tan \phi = [0 + (4500)(\pi/4)(0.06)^2 - 0.85] \tan(14.478^\circ)$$

$$F_t = 3.06 \text{ kN on major thrust side}$$

(c)

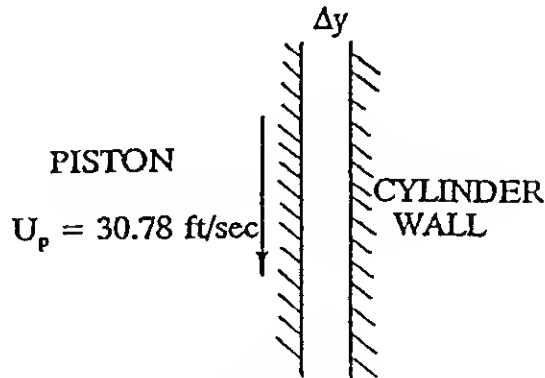
with wrist pin offset 2 mm

$$\sin \phi = 2.69/11.56 = 0.233$$

$$\phi = 13.456^\circ$$

$$F_t = [0 + (4500)(\pi/4)(0.06)^2 - 0.85] \tan(13.456^\circ) = 2.84 \text{ kN}$$

(11-4)



clearance between piston and wall

$$\Delta y = (3.1203 - 3.12)/2 = 0.00015 \text{ in.} = 0.0000125 \text{ ft}$$

Eq. (11-13)

$$\tau = \mu(\Delta u/\Delta y) = (0.000042 \text{ lbf-sec/ft}^2)[(30.78 \text{ ft/sec})/(0.0000125 \text{ ft})] = 103.42 \text{ lbf/ft}^2$$

force on piston with interface surface area $A = \pi B(\text{height})$

$$F = \tau A = (103.42 \text{ lbf/ft}^2)[\pi(3.12/12 \text{ ft})(2.95/12 \text{ ft})] = 20.8 \text{ lbf}$$

(11-5)

(a)

Eq. (2-88)

$$828 = (1000) \dot{W}_b(2)/(2.8)(2000/60)$$

$$\dot{W}_b = \underline{38.64 \text{ kW}}$$

(b)

using Eq. (2-37) at 1000 RPM

$$\text{imep} = \text{bmep}/\eta_m = (828 \text{ kPa})/0.90 = 920 \text{ kPa}$$

$$\text{fmep} = \text{imep} - \text{bmep} = 920 - 828 = 92 \text{ kPa}$$

at 2000 RPM

$$\text{imep} = (828 \text{ kPa})/0.88 = 941 \text{ kPa}$$

$$\text{fmep} = 941 - 828 = 113 \text{ kPa}$$

at 3000 RPM

$$\text{imep} = (646 \text{ kPa})/0.82 = 788 \text{ kPa}$$

$$\text{fmep} = 788 - 646 = 142 \text{ kPa}$$

Eq. (11-12)

$$\text{fmep} = A + B N + C N^2$$

$$92 = A + 1000 B + 1,000,000 C$$

$$113 = A + 2000 B + 4,000,000 C$$

$$142 = A + 3000 B + 9,000,000 C$$

$$A = 79 \quad B = 0.009 \quad C = 0.000004$$

at 2500 RPM

$$\text{fmep} = 79 + (0.009)(2500) + (0.000004)(2500)^2 = \underline{126.5 \text{ kPa}}$$

(c)

Eq. (2-88)

$$126.5 = (1000) \dot{W}_r(2)/(2.8)(2500/60)$$

$$\dot{W}_r = \underline{7.38 \text{ kW}}$$

(11-6)

(a) fuel rate

$$\begin{aligned}\dot{m}_f &= (65 \text{ miles/hr}) / (21 \text{ miles/gal}) = 3.095 \text{ gal/hr} \\ &= (3.095 \text{ gal/hr}) (46.8 \text{ lbm/ft}^3) / (7.481 \text{ gal/ft}^3) = 19.36 \text{ lbm/hr}\end{aligned}$$

oil use rate

$$\dot{m}_{oil} = (3.095 \text{ gal/hr}) / 40 = \underline{0.0774 \text{ gal/hr}}$$

(b) using time rate form of Eq. (5-26) for mixture trapped

$$\begin{aligned}\lambda_{tr} &= 0.64 = \dot{m}_w / [V_d \rho_s (N/n)] \\ &= \dot{m}_w / \{ [110 / (12)^3 \text{ ft}^3/\text{cycle}] (0.0739 \text{ lbm/ft}^3) (1850/60 \text{ cycle/sec}) \}\end{aligned}$$

$$\dot{m}_m \text{ trapped} = 0.0928 \text{ lbm/sec}$$

fuel trapped with 0.06 exhaust residual and AF = 17.8

$$\dot{m}_f = (0.0928 \text{ lbm/sec}) (0.94) (1/17.8) = 0.00464 \text{ lbm/sec} = 16.71 \text{ lbm/hr}$$

fuel flow time rate form of Eq. (5-24)

$$\lambda_{tr} = \dot{m}_m / \dot{m}_f = 16.71 / 19.36 = 0.863 = \underline{86.3\%}$$

(c) $(\dot{m}_{oil})_{ex} = \dot{m}_{oil} (1 - \lambda_{tr})$

$$(0.0774 \text{ gal/hr}) (1 - 0.863) = \underline{0.0106 \text{ gal/hr}}$$

(11-7)

(a) Eq. (3-31)

$$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/9.2)^{0.35} = 0.540 = \underline{54.0\%}$$

(b) with supercharger

$$\eta_t = (54.0) (1 - 0.06) = \underline{50.8\%}$$

(c) \dot{Q}_{in} will be proportional to air flow in \dot{m}_a

indicated power

$$\dot{W}_i \propto \eta_t \dot{Q}_{in}$$

$$(\dot{W}_{with \text{ s.c.}}) / (\dot{W}_{without}) = (\eta_t \dot{Q}_{in})_{with} / (\eta_t \dot{Q}_{in})_{without} = [(0.508)(1.22)] / [(0.540)(1.00)] = 1.148$$

14.8% increase with supercharger

(d) increase in brake power

$$(1.148) (1 - 0.04 \text{ to drive s.c.}) = 1.102 = \underline{10.2\% \text{ increase}}$$